EARTHQUAKES

AND OTHER EARTH MOVEMENTS

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BY

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in the Imperial College of Engineering, Tokyo,
Japan, 1876–95

NEW EDITION

Revised and Rewritten by

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Earthquakes and Other Earth Movements

THIS book was for many years the standard work on seismology. Since the author's death developments in this field have been so fundamental that his book has been superseded by others published in other countries and a new English work was overdue. Dr Lee has followed as closely as possible the classification adopted by Milne in the original edition, but he has ably rewritten almost all the sections dealing with instrumental seismology and considerably revised the remainder of the work.

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PREFACE

THE great progress which has been made in the scientific study of earthquakes during the last sixty years is largely due to the pioneer work of John Milne, who had such excellent opportunities for observing earthquake phenomena from 1876 to 1895 whilst he was a Professor in the Imperial University of Tokyo. Milne made the most of these opportunities, and the recognition of earthquake study as a quantitative physical science is due, in no small measure, to the investigations which he carried out in Japan and after he returned to England.

Milne's volume *Earthquakes and Other Earth Movements*, written in 1883, was for many years one of the standard works on the subject ; the book passed through six editions with only minor alterations, the sixth edition being published in 1913, the year in which Milne died. Two editions of a supplementary volume, *Seismology*, appeared in 1898 and 1908 respectively.

The development of seismology has continued since Milne's death. Much has been learned about the nature of earthquakes, the significance of the records, and about the materials inside the earth ; new problems have arisen in designing large buildings which would be immune from damage by earthquakes, and in satisfying the increasing demand for insurance against these calamities ; seismic methods have been successfully applied to the problems of locating oil and other deposits in the earth.

The developments are so fundamental that Milne's books have been superseded by those published more recently in other countries, and a new English work was needed. I therefore welcomed the invitation of Messrs. Kegan Paul,

Trench, Trubner and Co., to prepare this volume. In this new edition the classification of the various branches of the subject follows, as closely as possible, that adopted by Milne in 1883. It has been necessary, however, to rewrite almost all of the sections dealing with instrumental seismology and its applications, and most of the other parts of the book have been subject to considerable revision.

Much of the information given in this book has been acquired in connexion with the official duties of Kew Observatory, a part of the Meteorological Office, Air Ministry. I am indebted to the Director of the Meteorological Office for permission to undertake the preparation of the volume, and to include the copies of Kew seismograms shown in Figs. 21, 34, 37, 42 and 45. It is a pleasure to place on record my appreciation of the help and encouragement I have received from Dr. F. J. W. Whipple, the Superintendent of Kew Observatory.

Finally I have to acknowledge, with thanks, the permission to use illustrations from various sources. Figs. 24, 25, 74, 75 and 76 are reproduced from Geophysical Memoirs by permission of the Controller of H.M. Stationery Office. The Royal Astronomical Society, with the concurrence of Dr. Whipple and Dr. E. C. Bullard, has granted permission for Figs. 62, 66, 73, 79, 80 and 81 to be copied from papers published in the Geophysical Supplement to its Monthly Notices. Miss E. F. Bellamy has allowed me to include (Fig. 55) a copy of the map of epicentres given in her *Catalogue of Epicentres for 1913–30*; in this map the epicentres are shown on a Mollweide world background prepared by Messrs. E. Stanford, Ltd., who have allowed me to use similar outline maps for Figs. 56 and 59. Mr. J. J. Shaw kindly supplied the photograph of the Milne-Shaw instrument (Fig. 23), and the Rev. J. P. Rowland, S.J., was good enough to place at my disposal the Stonyhurst seismogram reproduced in Fig. 33.

A. W. LEE.

October, 1938.

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EARTHQUAKES

CHAPTER I

INTRODUCTION

EARTHQUAKES have attracted universal attention from the earliest times, and on account of their destructive power it is not surprising that they used to be regarded as supernatural phenomena. Among the earliest existing records of earthquakes are those mentioned in the Bible. The writings of Herodotus, Pliny, Livy, etc., also show the interest which earthquakes attracted in early ages. These writers chiefly devoted themselves to references and descriptions of disastrous shocks, and to theories respecting the cause of earthquakes. The greater portion of the Japanese notices of earthquakes is simply a series of anecdotes of events which took place at the time of these disasters. In addition there are references to superstitious beliefs, curious occurrences, and the apparent connexion between earthquake disturbances and other natural phenomena; in these respects the literature of the East closely resembles that of the West. Speaking generally, it may be said that the writings of the ancients, and those of the Middle Ages, down to the commencement of the nineteenth century, tended to the propagation of superstition and to theories based on speculations with few and imperfect facts for their foundation.

The development of the study of earthquakes on a rational basis may be regarded as dating from the nineteenth century.

Professor A. Perrey, of Dijon, in 1840, commenced a series of extensive catalogues embracing the earthquakes of the world. This work was taken up by R. Mallet, a leading engineer in Dublin, who published a great catalogue of nearly seven thousand earthquakes in the Reports of the British Association for the years 1852–4. The facts thus accumulated enabled Mallet to discuss earthquakes in general, and to classify the various phenomena which are associated with them. Another great impetus which observational seismology received was Mallet's report upon the Neapolitan earthquake of 1857, in which he described new methods for use in seismic investigations. Many observers in later years adopted these methods, and by them, as well as by his experiments on artificially produced disturbances, Mallet finally drew the study of earthquakes from the realms of speculation by showing that they, like other natural happenings, were capable of being understood and investigated.

Some years later great progress in the study of the phenomena was made by a number of British scientists resident in Japan. The leader of the group was John Milne, Professor of Mining, Geology, and Seismology in the Imperial College of Engineering, Tokyo, from 1876 to 1895, and the author of the volumes *Earthquakes* and *Seismology* which have been incorporated in this work. Milne and his collaborators, among whom were such famous scientists as W. E. Ayrton, J. Perry, J. A. (later Sir Alfred) Ewing, C. G. Knott, and T. Gray, were responsible for the formation in 1880 of the Seismological Society of Japan. The members of the Society obtained numerous observations of the effects of earthquakes over large areas, and constructed many ingenious instruments by which the ground movements due to the shocks could be recorded. Accounts of their researches are given in the Transactions of the Society, and in the *Seismological Journal of Japan.*

Towards the end of his stay in Japan Milne became interested in the recording of distant earthquakes, and on

his return to England he set up an observatory at Shide in the Isle of Wight, and began to lay the foundations of a world-wide network of observatories for earthquake recording. He had designed a new type of seismograph and instruments of this sort were set up at a number of stations in different parts of the world; the information obtained from the records was collected at Shide for inclusion in Milne's lists of earthquakes which were published by the British Association for the Advancement of Science. The work suffered a great blow from the death of Milne on 31st July, 1913, but was carried on by Professor H. H. Turner, Savilian Professor of Astronomy in the University of Oxford from 1893 to 1930, who had been associated with Milne's work for the Seismological Committee of the British Association. Thus the University Observatory at Oxford became the international centre for the collection and publication of the observations of earthquakes. Since Turner's death the work has been continued at Oxford under the direction of his successor, Professor H. H. Plaskett. The amount of material available has increased enormously, for there are now nearly five hundred seismological observatories in different parts of the world, and the lists of earthquake observations published from Oxford, and known as the *International Seismological Summary,* run into about five hundred pages per annum.

During the last forty years, while this world-wide network of observatories for recording earthquakes has been developing, great improvements have been made in the design of the instruments and towards the study of earthquake waves. Among the most popular instruments designed during this period are the Milne-Shaw, which was evolved from the original Milne type, the inverted pendulums of E. Wiechert, Galitzin's aperiodic pendulums with electromagnetic registration, and the high magnification seismographs constructed in 1925 by J. A. Anderson and H. O. Wood.

Definitions

The science of seismology, named from the Greek *σεισμός*, an earthquake, and *λόγος*, a discourse, in its simplest form means the study of earthquakes, but it now embraces the study of other earth movements due to a variety of causes. The greater part of the present volume is devoted to the phenomena of natural earthquakes, but two types of other earth disturbances are included in Chapters XIV and XV. These are the minute ground movements known as microseisms or microseismic disturbances, and the artificial earthquakes caused by explosions and used in seismic prospecting ; the former are nearly always to be found in the records of sensitive seismographs and are associated with storms over the oceans.

The English word earthquake, the German *Erdbeben*, the French *tremblement de terre*, the Spanish *terremoto*, the Japanese *jishin*, etc., all mean " earth shaking " when literally translated. The terms are generally used to describe sudden and more or less violent disturbances of the earth's crust, and are appropriate for any such disturbances without regard to their severity. The source from which the earthquake originates is called the " focus ", and the region of the surface immediately above the focus is termed the " epicentre ". The time at which a shock occurs at the focus is referred to as the " time of origin " of the earthquake.

There are enormous variations in the areas over which earthquakes are perceptible and in the destructive effects which accompany the shocks. At one end of the scale are the great earthquakes felt over hundreds of thousands of square miles, and accompanied by great loss of life and extensive damage to property ; at the other are the small shocks only felt by a few people and over a very limited region. With increasing distance from the epicentre the disturbance gets less and less and eventually is imperceptible. The movements recorded by instruments at great distances

beyond the area in which the earthquake can be felt are said to be teleseismic.

The earth is very nearly spherical and so the distance from an earthquake to any place may be measured as an arc of a great circle.[1] In seismological work distances are usually expressed in degrees, representing the angle subtended by the arc at the centre of the earth, but sometimes they are measured along the surface in miles or kilometres. The relationships between the various systems of measurement are:

$$90^\circ = 10{,}000 \text{ km.}$$
$$1 \text{ mile} = 1{\cdot}6093 \text{ km.}$$

Scope of Seismology

Earthquakes and their effects are generally regarded as subjects to be studied by scientists and engineers. The treatment throughout this work will support that belief, but it must be remembered that the phenomena are of interest in other directions. In his *History of Civilisation in England* Buckle has laid considerable stress upon the manner in which earthquakes, volcanoes, and other of the more terrible forms in which the workings of nature are revealed to us, have exerted an influence upon the imagination and understanding; and just as a sudden fright may affect the nerves of a child for the remainder of its life, we have in the annals of seismology records which indicate that earthquakes have not been without a serious influence upon the mental condition of whole communities. The general temperament of a nation is no doubt largely due to its environment, and it is not unreasonable to suppose that serenity of demeanour and carelessness of the future, so typical of the eastern Asiatic races, may be related to repeated outbreaks of seismic and volcanic activity. There

[1] The shortest distance between any two points on a sphere is a "great circle"; it will be recalled that this is the circle drawn through the two points in the plane which contains the centre of the sphere.

are, however, so many causes which contribute to the development of racial characteristics that we cannot sort out the particular results due to any individual factors.

(The study of earthquakes is a branch of the modern science of geophysics, which, as its name implies, covers all the phenomena of the physics of the earth. The subject is naturally of much wider scope than the physics of the laboratory, and the geophysicist makes use of the results obtained from various branches of science and engineering. Seismology may be approached either from the geological or from the physical aspects.) To a geologist there are perhaps no phenomena in nature more interesting than earthquakes. He observes their effects upon the surface features of the earth, such as the displacements at faults, upheavals or subsidences of the ground, landslides, etc., and applies the results to tracing out the processes which must have operated to cause these changes, or to explaining the observations of corresponding characteristics in other regions. (On the physical side the seismologist is interested chiefly in the development of instruments for recording earthquakes, and in obtaining from the study of the records all the information he can about the earthquakes and about the materials inside the earth.) It has been found that the records of an earthquake not only give the location of the shock, but that, in addition, they show the depth beneath the surface at which the disturbance originates, and the type of movements which generate the shock. Also, since as the earthquake waves travel through the earth, they are affected by the materials at various depths, the records of the waves furnish information about the rocks through which they travel. Hence it is possible from the records of distant earthquakes to learn about the properties of the material right down to the centre of the earth. This information cannot be obtained in any other way.

(Seismology invites the co-operation of workers and thinkers in almost every department of science. Mathematicians are faced with many problems relating to the elasticity of

solids, the wave motion propagated from a disturbance, and the response of the instruments to applied oscillations of prescribed forms. To the astronomer earthquakes are disturbances which may occur on any planet, and the information they give about the interior of the earth is of value towards a better knowledge of the composition and conditions in other members of the solar system. Meteorologists, as well as seismologists, in many countries have interested themselves in the study of microseisms. The distribution of earthquakes throughout the world is of importance to geographers and those interested in the evolution of the different races of mankind. We may even include the students of natural history who examine the effects produced by earthquakes on the lower animals.

Turning to the more practical side of seismology, the greatest need has been to increase our knowledge of earthquakes so that we can lessen the destruction caused by them. For this purpose it is necessary to examine the effects of earthquakes upon buildings and the methods which should be adopted to avoid damage to the structures in earthquake-shaken countries. Here we are face to face with problems which demand the attention of engineers, architects, and builders. On the engineering side there are problems connected with the location and best methods of construction to be adopted for houses, factories, bridges, water-mains, etc. The results obtained from observations of earthquake damage are utilised by the architect in designing the buildings to be erected in seismic regions.

Seismological information is necessary when insurance companies are requested to cover property against earthquake damage. The rate of premium has to be based upon an estimate of the risk involved, and in gauging the risk it is necessary to consider the damage done by earlier earthquakes, and the frequency with which the earthquakes have occurred in different regions.

The construction of sensitive instruments for detecting the waves from earthquakes, and the study of these waves,

has led to the application of seismic methods to the problems of prospecting. The properties of the rocks near the earth's surface can be studied by these methods, and the results of the investigations are of value to geologists and in commercial work connected with the search for oil and for mineral deposits.

Chapter II

OBSERVATIONS OF EARTHQUAKE PHENOMENA

Reports of experiences during earthquakes, and of observations of the phenomena which accompanied the disturbances, have been published on many occasions. The information to be obtained from these reports is discussed in the following sections, but before classifying the phenomena, general descriptions will be given of two great earthquakes [1]; one of the earthquakes selected for this purpose is that which destroyed Caracas, the capital of Venezuela, on 26th March, 1812, the other is the New Zealand earthquake of 2nd February, 1931. Many other earthquakes have caused greater loss of life and material damage, but the reports for these shocks will be sufficient to show what terrible devastation has been caused, and to emphasize the need for incessant study of any precautions which may possibly mitigate the effects of future disasters.

The Caracas Earthquake of 26th March, 1812

The day rose fair and bright. The air was calm, the sky unclouded. Large numbers of the inhabitants were at church in attendance at the services, for it was Maundy Thursday. Suddenly the bells tolled without the touch of mortal hand. This was the first intimation of the earthquake which almost simultaneously was upon the unhappy people. The movement of the earth was from north to

[1] The description of the Caracas earthquake was published in the *Japan Gazette*, 10th March, 1880; that of the New Zealand earthquake has been prepared from the reports in the English newspapers.

south, with transverse jerks from east to west. These cross-agitations of the surface, occurring with extreme rapidity, instantly prostrated everything animate and inanimate. The inhabitants were unable to crawl to the church doors and these vast churches, which are characteristic of all South American cities from the largest to the smallest, descended in ruins around them. Ten thousand persons are said to have been killed in the churches alone. The churches of La Trinidad and Alta Gracia, more than one hundred and fifty feet in height, with naves supported by pillars of twelve and fifteen feet in diameter, were reduced to masses of ruin little more than a man's height. In the barracks a regiment of soldiers had just been drawn up under arms, ready to form part of a procession that was to take place after divine service. Scarcely a man of them was left. And all this was the work of a single minute. From the first tolling of a bell to the falling of the last stone of the city of Caracas one minute only elapsed.

Many thousand persons were wounded, for whom there was no shelter, no medicine, no food, scarcely a drop of water. There were not even implements wherewith to extricate them from the ruins which lay upon them. The survivors dug out with their fingers two thousand of their crushed fellow citizens who had still some life remaining in them. The shock had broken the pipes conveying water; the falling in of the earth had choked up the springs which supplied them, there were no utensils wherewith to carry water from the river. The wounded and sick were carried to the river's bank and there left under such protection as the foliage afforded. The night we are told rose calm and serene, the round full moon shone over the labours of the survivors. Mothers still carried their dead children about, refusing to believe that life had entirely fled. Troops of relatives and friends sought for missing ones up and down streets, now to be traced only by long lines of ruins. A sterner duty yet remained. Twelve thousand dead bodies lay around, and decomposition within the tropics may be

said to begin at the moment of death. There were no means of digging graves; the bodies must be burnt and that at once. Bands of citizens were set apart for this only. Vast piles of timber from the ruins of their houses were raised at frequent intervals; bodies of fathers, husbands, wives, children were laid on them; and soon the whole sky was lighted with these awful flames. This lasted for several days, during which the survivors strictly devoted themselves to religious exercise. Some sang hymns, others confessed crimes, of which they had never been suspected; numbers made what compensation was in their power.

The New Zealand Earthquake of 2nd February, 1931

This earthquake, which was felt over the whole of New Zealand, originated near the coast of Hawke's Bay on the east side of the North Island at 10 h. 17 m. New Zealand time on 3rd February, 1931; since the standard time for New Zealand is 11½ hours later than Greenwich, the shock occurred at 22 h. 47 m. G.M.T. on February 2nd. The chief pursuits in the neighbourhood around Hawke's Bay are agriculture and grazing, with the cities of Napier and Hastings as the business centres; large quantities of wool and frozen mutton are exported from Napier. The damage caused by the earthquake was much more severe at Napier on the coast than at Hastings some 20 km. away. The fires and landslides which followed the earthquake added to the damage, and the casualty lists amounted to 255 people killed and about 1,500 injured. The region in which there was serious damage and loss of life extended over a large area from Gisborne in the north-east to Wanganui on the west side of the island.

The shock was preceded by a low rumbling sound. The most violent movements of the ground lasted from one to two minutes, but in that time walls and houses collapsed, blocking the streets with débris and reducing the cities almost to ruins. In Napier there were numerous casualties,

and nearly all the business area was damaged (see Fig. 1). After the earthquake fires broke out and could not be extinguished at once, the supply of water having failed owing to breakages of the mains; warehouses and their contents were destroyed in the fires. Pavements and roads were broken and the ground over the whole of the surrounding region was traversed by cracks and fissures (Fig. 2). Great masses of earth, carried down from the cliffs amid clouds of dust, buried motor cars with the people still inside them, and damaged the harbour. The sea bed in the harbour was raised by about two metres, and even small boats were unable to approach close to the shore. Communications by train or telegraph were cut off owing to the buckling of the rails (Fig. 3) and destruction of railway bridges and of the telegraph lines.

The earthquake was followed by general confusion but there was no panic and rescue parties were organised as quickly as possible. The commander of H.M.S. *Veronica*, which was in Napier harbour at the time, took charge of the relief work and sent out bluejackets who were joined by parties from the liners *Taranaki* and *Northumberland*. The warships *Diomede* and *Dunedin* were sent from Auckland by the New Zealand Government with supplies for the injured and homeless.

Nearly all of the finest buildings in Napier were damaged or destroyed. Business premises, the Municipal theatre, and schools were reduced to ruins. The Cathedral, after being severely damaged by the shock, took fire. Among the residents in a home for elderly people, ten aged from 80 to 100 were killed, and twice that number of students perished in the ruins of one of the schools. The hospital and nurses' home were destroyed; many nurses lost their lives in the wreckage but most of the patients were saved. Six nurses were saved from the nurses' home, two of them having suffered silently for hours while the naval men with crowbars and sledgehammers removed the great blocks of concrete under which they were imprisoned. Temporary

hospitals and dressing stations for the injured were opened in the parks and in undamaged buildings. A brighter spot among the tales of suffering is the report that, at the Salvation Army maternity home in Napier, bricks from a chimney fell in the cradles of five babies but none was injured.

Even if their houses were still habitable people were afraid to go home at night, and many gathered on the beaches near the city. The general alarm was increased by the frequent smaller shocks which followed the earthquake; there were 151 of these shocks on the day of the earthquake, and 55 on the following day; they recurred at irregular intervals for several months.

After the earthquake the city of Napier had to be evacuated, owing to the risk of an epidemic following the breakdown of the water supplies and other public services. The Sunday following the disaster was observed as a day of mourning and intercession in all the churches throughout New Zealand.

Movements Experienced during an Earthquake

The sensations experienced during an earthquake depend upon many factors such as the severity of the shock, the distance from the epicentre, the geological structure in the vicinity of the observer, and the conditions of observation. Generally it feels as if the ground is undergoing a series of backward and forward movements in quick succession. These oscillatory movements may commence and die down so gently that those who have endeavoured to time the duration of an earthquake have found it difficult to say when the shock commenced and when it ended. The movements may gradually increase to a maximum and then die out as gradually as they commenced, or the maximum may come suddenly as a jolt; at other times during an earthquake it feels as if the motion increases and dies down several times in succession.

These have been the experiences of many observers, and have been recorded by writers since the earliest times. Mallet devotes a chapter to a consideration of the motion that precedes and follows a shock, and he expresses the opinion that a single shock is an absolute impossibility. In speaking of earthquakes, he says: "The almost universal succession of phenomena recorded in earthquakes is, first a trembling, then a severe shock, or several in quick succession, and then a trembling."

It is well known that persons feeling the motion of the ground during an earthquake are often subject to a feeling of nausea or giddiness, somewhat akin to a mild form of sea-sickness. This is most frequently experienced in regions beyond the zone of the destructive effects and where the earth motion is slower and more rhythmical. These feelings have been reported, however, by some observers nearer to the epicentre, but here the nausea may have resulted from the nervous shock rather than from the ground movements. The symptoms frequently persist for several hours after the perceptible motion of the ground has ceased. These effects have been noticed from a number of the earthquakes felt in this country. For the Hereford earthquake of 17th December, 1896, they were reported from many districts including some, such as Bradford, London, and Weymouth, over a hundred miles from the epicentre. Nausea was also reported by a few people in the South of England on the occasion of the recent Belgian earthquake of 11th June, 1938, which was felt in this country.

One of the most ordinary observations which are made about an earthquake is its direction. If we were to ask the inhabitants of a town which had been shaken by an earthquake the direction of the motion they experienced, it is not unlikely that their replies would include all the points of the compass. Many, in consequence of their alarm, have not been able to make accurate observations. Others have been deceived by the motion of the building in which they were situated. Some tell us that the motion had been

north and south, whilst others say that it was east and west. A certain number have recognized several motions, and amongst the rest there will be a few who have felt a wriggling or twisting. Leaving out exceptional cases, the general result obtained from personal observation as to the direction of an earthquake is very indefinite. Mallet endeavoured to locate the position of the origin of the Neapolitan earthquake from observations of the direction in which walls, columns and other objects had been overturned or fractured. These effects have been studied for many other earthquakes and it has been found that the direction in which pillars are overturned does not necessarily show the direction of the epicentre ; we now recognize that the inconsistencies in these observations are due to the complicated nature of the ground movements which cause the damage, and that the only satisfactory way to determine the direction of the movements is from the records of instruments.

Sounds Associated with Earthquakes

Nearly all widely observed earthquakes have been preceded, accompanied, or followed by sounds, the nature of which has varied with the position of the observer and the locality in which he has been situated. They have been described as being like thunder, the rattle of musketry, the rumbling of a heavy vehicle, the escape of steam, etc. Generally the sound is very low and so near to the threshold of audition that it is heard by some observers and missed by others. The sound always appears to come from the ground beneath the observer and is more frequently noticed in mountain districts than in the plains. C. G. Knott, in explaining that these sounds are produced by the rapid vibrations of the ground, pointed out that the sound waves in air travel much more slowly than the waves in the ground ; as a consequence the waves leaving the ground are refracted nearly vertically upwards whatever their

direction of incidence beneath the surface, and the sound always appears to come from below.

After the Mino-Owari earthquake of 28th October, 1891, at a distance of from 10 to 20 miles from the epicentre, booming sounds were heard every few minutes. The sounds preceded small shocks by intervals of one or two seconds. Sometimes the shock and the sound were simultaneous, and often there were sounds without shocks.

The descriptions of the earthquakes felt in Britain nearly always include reports of sounds which accompanied the shocks. According to Dr. C. Davison, the great authority on British earthquakes, the sounds are heard by 97 per cent of all the observers for the slight shocks, in which the dominant feature is the sound rather than the shaking or jolting, and by 83 per cent of the observers for the stronger shocks. The percentage of observers hearing the sounds falls off as the distance from the epicentre increases; the diminution is small in regions near the epicentre, but becomes rapid near the boundary of the region over which the sounds are audible.

Reactions of Animals to Earthquake Movements

There are many reports of the behaviour of animals during earthquakes. Horses become excited, whinnying or snorting at first, stampeding during the larger movements and occasionally losing their balance and falling. Cows, if not thrown to the ground, stampede and run about wildly; lowing and bellowing of the cattle are commonly reported. Cats and dogs are alarmed and often run wild, their behaviour depending largely upon their temperaments—some are aggressive whilst others are cowed. The most common report of the behaviour of dogs at the time of the San Francisco disaster of 1906 was that they howled during the night preceding the earthquake, implying that they sensed the impending disaster. It is very difficult to accept such a suggestion, for there is no scientific explana-

tion as to why dogs should have been gifted with these premonitions.

The belief that animals could give warning of coming earthquakes is a very old one. It used to be said that several of the natives of Caracas possessed oracular quadrupeds, such as dogs, cats, and jerboas, which anticipated coming dangers by their restlessness. Before the Caracas earthquake referred to earlier in this chapter (p. 9), a Spanish stallion broke out from its stable and escaped to the highlands, which was regarded as the result of the prescience of a coming calamity. Before the disturbances of 1822 and 1835 which shook Chile, immense flocks of sea-birds flew inland, as if they had been alarmed by the commencement of some sub-oceanic disturbance. It is also related that, before the latter of these shocks, all the dogs escaped from the city of Talcahuano.

Very often it is stated that animals show signs of alarm a few seconds before an earthquake is perceptible to human beings. Possibly the animals, either lying down or with their feet in direct contact with the ground, are affected by very small movements which we do not feel and which outrun the larger oscillations. Some reports have suggested that the time-interval is longer than a few seconds, but the estimates of these intervals are vague owing to the general excitement when an earthquake is felt.

There is a widespread belief in Japan that pheasants are sensitive to tremors which are imperceptible to human beings. Professor F. Omori, who was very favourably situated for noticing small disturbances whilst studying during the quiet hours of the night, observed twenty-two occasions when pheasants crowed in a nearby garden. He found that the birds were generally disturbed by movements caused by earthquakes, but not by the vibrations which were due to traffic in the vicinity. On about half of the occasions Professor Omori could not feel the tremors which disturbed the birds, but the seismic nature of the movements was confirmed from the records of instruments. On seven of

the occasions when the motion could be felt the pheasants crowed several seconds before it was perceptible. The sensitivity of pheasants to minute disturbances has also been noticed in this country, where the birds have sometimes been disturbed by the atmospheric oscillations caused by distant gunfire.

Duration of an Earthquake

When reading accounts of earthquakes it is often difficult to determine the length of time during which the ground was in motion. Continuous motions perceptible to our senses without the aid of instruments usually last from several seconds to a few minutes, but in many earthquakes the sensations experienced are almost instantaneous, being described as a single bump or jolt. Milne found that in Japan the shocks, as timed by watches, generally lasted from 20 to 40 seconds, but occasionally the shaking was continuous for more than a minute. The estimates of the duration of the motion during the Long Beach (California) earthquake of 10th March, 1933, range from about 5 to 35 seconds, with the most violent movements lasting for less than 15 seconds. On the occasion of the Belgian earthquake, which originated near Ghent at 10 h. 57 m. G.M.T. on 11th June, 1938, it was generally reported that the movements felt in Britain and on the continent only lasted for a few seconds.

Only the rapid movements of the ground can be felt, but actually the motion lasts for a much longer time ; the later oscillations, however, are slower and the movements are too small to be noticed. The duration of an earthquake, measured from the record of a seismograph, depends upon the sensitivity of the instrument. Some instruments are very sensitive to the slower oscillations and their records show that the disturbances generated from a great earthquake do not die down for several hours.

In seismic regions the shocks sometimes succeed each

other so rapidly that the movements overlap. In Japan in A.D. 745, there was a shaking which is said to have lasted sixty hours; and in A.D. 977 there were a series of shakings lasting 300 days. Often we meet with reports of disturbances which have lasted for several months with only brief interruptions. At San Salvador, in 1879, more than 600 shocks were felt within ten days; in 1850, at Honduras, these were 108 shocks in a week; in 1746, at Lima, 200 shocks were felt in twenty-four hours. More recently there has been a notable spell of seismic activity in the island of Montserrat, British West Indies, which became most severe in November, 1935; during that month about 600 shocks were experienced. The disturbances were all small except the outstanding shock on 10th November, which originated some distance from the island and was large enough to be recorded by seismographs in all parts of the world. This earthquake was followed by a conspicuous decline in the frequency of the shocks in Montserrat.

Disturbances which succeed each other with sufficient rapidity to cause an almost continual trembling of the ground may be regarded as collectively forming one great seismic effort which may last a minute, an hour, a day, a week, or even several years. Strictly speaking, they are a series of separate earthquakes, the resultant vibrations of which more or less overlap. Whenever a large earthquake occurs it is generally succeeded by a large number of smaller shocks in the same region; these later disturbances are known as aftershocks. Less frequently a great earthquake is preceded by a number of smaller disturbances which are termed foreshocks.

The aftershocks are most numerous immediately after the main earthquake, and although the frequency gets less as the time interval increases, the series of disturbances may persist for several years. The aftershocks of the Mino-Owari earthquake of 28th October, 1891, have been tabulated by F. Omori, who finds that 3,365 of these disturbances were recorded during an interval of 26 months at Gifu, about

25 km. from the region of greatest disturbance; of the aftershocks 318 occurred on the day following the earthquake, 720 before the end of October, and 1,746 during the first thirty days. In studying the aftershocks Omori summarized the numbers which were recorded in successive intervals of time. The rapid decline in the frequencies shortly after the earthquake and the subsequent irregular variations are brought out from the following table, in which are given the numbers of shocks at Gifu for each month up to December, 1893.

MONTHLY NUMBERS OF EARTHQUAKES AT GIFU, 28TH OCTOBER, 1891, TO 31ST DECEMBER, 1893

Month	*Earthquakes*	*Month*	*Earthquakes*
1891, October (28–31)	720	1892, December	39
November	1,086	1893, January	31
December	421	February	20
1892, January	164	March	52
February	114	April	59
March	87	May	32
April	90	June	12
May	54	July	18
June	30	August	13
July	35	September	20
August	52	October	19
September	107	November	16
October	47	December	16
November	48		

Omori found that, apart from minor irregularities which are due to the aftershocks sometimes occurring in groups, the rates of diminution in the frequencies could be represented by empirical formulæ of the type $N = \frac{C_1}{t + C_2}$; in these formulæ N represents the number of aftershocks, t the time measured from the earthquake, and C_1 and C_2 are constants. Formulæ of Omori's type have been obtained for the distribution of the aftershocks following other earthquakes.

The great Japanese earthquake of 1st September, 1923, which destroyed Tokyo and Yokohama and caused the loss of nearly a hundred thousand lives, was followed within a month by 1,256 aftershocks, and more than half of these

aftershocks were strong enough to be felt. The aftershocks following the New Zealand earthquake in 1931 have been mentioned earlier in this chapter; the total number recorded at Hastings up to the end of 1931 amounted to 938, the numbers for the six months after the earthquake being:

February,	596	May,	44
March,	78	June,	42
April,	50	July,	28

The epicentres of the aftershocks following a great earthquake are scattered over a considerable area.

Scales of Seismic Intensity

The intensity of an earthquake in any part of the disturbed area may be gauged from the effects upon persons and objects, or from the amount of damage caused by the shock. The procedure adopted in examining these effects is to classify them according to an arbitrary scale in which the different grades are related to the severity of the earth movements. Each grade in the scale is distinguished by a number of typical effects which are commonly noticed if the earthquake reaches the prescribed intensity. Many scales of this sort have been devised. One of the oldest was prepared by P. Macfarlane, a postmaster at Comrie in Perthshire, for comparing the intensities of the numerous earthquakes which occurred in that district about a hundred years ago; on this scale I, the lowest grade, represented the slightest perceptible shock, and X, the highest, corresponded with the intensity of the most severe earthquake of the series, which occurred on 23rd October, 1839, and was felt over nearly all Britain.

Following the preparation in 1873 by M. S. Rossi of a scale for Italian earthquakes, and some years later of one for Swiss earthquakes by F. A. Forel, these two authorities collaborated in drawing up a single scale which is known as the Rossi-Forel scale of 1883. This scale has been used more generally than any other. The specification of the

effects for the ten grades of the Rossi-Forel scale are given below.

ROSSI-FOREL SCALE OF SEISMIC INTENSITY

I. Noticed by an experienced observer.
II. Noticed by a few people at rest.
III. Generally felt by people at rest.
IV. Felt by people in motion. Doors and windows rattle.
V. Felt generally. Disturbance of furniture.
VI. Hanging objects such as chandeliers set in motion. Clocks stopped. Sleepers wakened.
VII. Causes panic. Movable objects overthrown. Church bells ring.
VIII. Damage to buildings. Chimneys fall and walls are cracked.
IX. Some buildings destroyed.
X. Widespread destruction.

Although the Rossi-Forel scale has been so widely used, it has been criticized on the grounds that the various grades are unequally spaced, and that the distinctions between them are too indefinite. An alternative scale for modern use was introduced in 1931 by H. O. Wood and F. Neumann. This scale was based upon earlier ones due to G. Mercalli, A. Cancani, and A. Sieberg. It is divided into twelve grades, and the descriptions given for the effects in each of the grades are very comprehensive. The chief characteristics of the grades, and the corresponding intensities of the Rossi-Forel scale, are set out in the following form.

MODIFIED MERCALLI INTENSITY SCALE OF 1931 (*Abridged*)

I.	Not felt except by a very few under especially favourable circumstances.	R.F. I
II.	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.	R.F. I–II
III.	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor-cars may rock slightly. Vibrations like passing of lorry. Duration estimated.	R.F. III

IV.	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed ; walls make cracking sound. Sensation like heavy lorry striking building. Standing motor-cars rocked noticeably.	R.F. IV–V
V.	Felt by nearly everyone ; many awakened. Some dishes, windows, etc., broken ; a few instances of cracked plaster ; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.	R.F. V–VI
VI.	Felt by all ; many frightened and run outdoors. Some heavy furniture moved ; a few instances of fallen plaster or damaged chimneys. Damage slight.	R.F. VI–VII
VII.	Everybody runs outdoors. Damage negligible in buildings of good design and construction ; slight to moderate in well-built ordinary structures ; considerable in poorly built or badly designed structures ; some chimneys broken. Noticed by persons driving motor-cars.	R.F. VIII
VIII.	Damage slight in specially designed structures ; considerable in ordinary substantial buildings with partial collapse ; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor-cars.	R.F. VIII–IX
IX.	Damage considerable in specially designed structures ; well designed frame structures thrown out of plumb ; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.	R.F. IX

X.	Some well-built wooden structures destroyed; masonry and frame structures and their foundations destroyed; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed over banks of rivers, etc.	R.F. X
XI.	Few, if any, masonry structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and landslips in soft ground. Rails bent greatly.	—
XII.	Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown upward in the air.	—

If the intensities at various points are marked on a map of the disturbed region, lines can be drawn to include all places at which the disturbance exceeds the various graduations of the intensity scale in use. These are the isoseismal lines, and correspond with the contours of a physical map, or with the isobars of a synoptic weather chart. As a result of a simple disturbance at a point in a homogeneous medium, we ought, theoretically, to obtain equal mechanical effects at places on the surface of the medium at equal distances from the disturbance, and the isoseismal lines would be circular. This is not found to be the case in practice, for owing to heterogeneity in the earth's composition the isoseismal lines are generally irregular or elliptic in shape. The isoseismal lines corresponding with Rossi-Forel intensities IV, VI, VIII and X for the Hawke's Bay earthquake are shown in Fig. 4. In the central region the line X is roughly oval and in the direction from north-east to south-west. The outer isoseismal lines are not so regular, especially in the south island; this would be expected since the criteria for the higher grades, being based on observations of the damage caused by the earthquake, are less arbitrary than those of the lower grades which depend on the results of individual experiences.

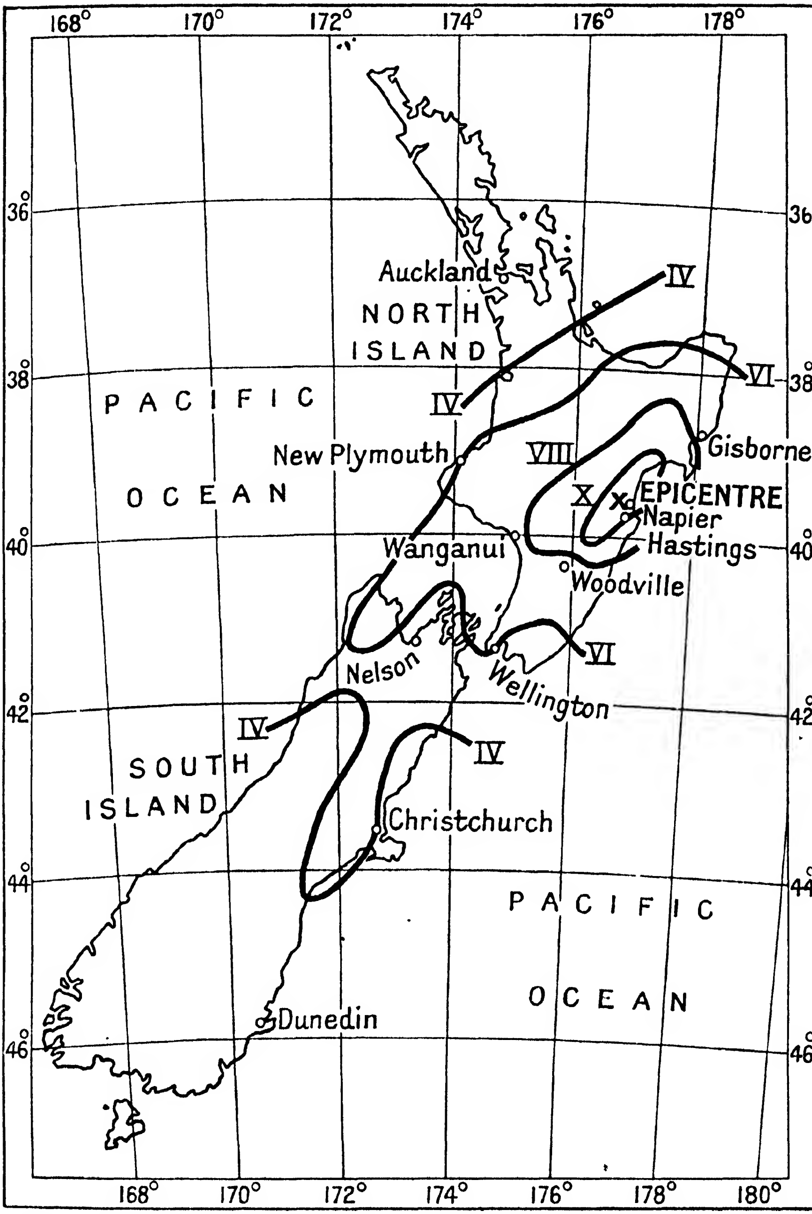


FIG. 4.—Isoseismal lines for the New Zealand earthquake of 2nd February, 1931 (Adams).

Chapter III

SOME EFFECTS OF EARTHQUAKES

In this chapter we shall consider the changes produced by earthquakes in the topographic, oceanographic and geological features of the epicentral regions, and some of the natural phenomena occasionally associated with the disturbances. Among the latter, the most important are the dreaded "tunamis" which have been responsible for some of the most terrible earthquake disasters.

Effects on Land

Although most of the great earthquakes originate at depths of about 30 km. beneath the earth's surface, the disturbances are frequently large enough to produce noticeable changes in the weaker rocks visible at the surface. Many observations have been made of these superficial movements, but we do not know how far they extend beneath the surface or whether there are corresponding changes at the greater depths. Among the effects which have been attributed to earthquakes are the formation of faults [1] and fissures in the ground, displacements in the vicinity of faults, the uplift or subsidence of tracts of country, and landslips.

Earth movements in the vicinity of faults may on occasions be traced over very great distances. The best-known case is that of the earthquake which wrought such havoc in

[1] A fault is a discontinuity in the crust of the earth, representing a fracture where the regions on one side have been displaced relatively to those on the other side. The regions on either side of the fracture are sometimes of very great extent.

San Francisco on 18th April, 1906; the earthquake was attributed (*Report of the State Earthquake Investigation Commission*, Vol. i, p. 2) to a sudden rupture of the earth's crust extending over a distance of about 430 km. from around Point Delgada to the region of San Juan. The line of dislocation runs roughly from north-west to south-east. At the time of the shock the ground on the south-west side of the line was raised and displaced in a north-westerly direction relative to that on the other side. The vertical movement was less than a metre, but the horizontal movement probably exceeded three metres over the greater part of the distance; in many regions it was about five metres, and in one place it was nearly seven metres. Fig. 5 is taken from the above-mentioned Report to illustrate the movement, and shows a fence near Woodville which was severed and displaced sideways through a distance of 3½ metres.

The Mino-Owari earthquake of 1891, and the Formosa earthquake of 17th March, 1906, are other examples of shocks accompanied by considerable movements along faults; the length of the fault is about 100 km. for the earlier earthquake, and about 50 km. for the latter. The uplift of the ground for the Mino-Owari earthquake was from three to seven metres, being roughly equal to the horizontal displacement; the photograph of Fig. 6 shows the fault crossing a road near Midori, in a region where the relative displacements between the two sides of the fault amounted to about six metres vertically and four metres horizontally. For the Formosa earthquake the displacements were smaller, only amounting to two or three metres.

According to Dr. Davison the greatest vertical displacement on record is that of 14½ metres (47 ft. 4 in.), on the north-east shore of the Yakutat Bay in Alaska, which was caused by the earthquake on 10th September, 1899. The elevation of the coast-line due to the earthquake was estimated from the heights above sea-level to which the rocks were subsequently found encrusted with the shells of dead

barnacles. These observations at once gave the changes in height, for the living barnacles are only attached to rocks under the water.

In the records of Indian earthquakes we find that the Cutch earthquake of 16th June, 1819, was accompanied by the development of a mound or embankment which is supposed to follow the fault on which the earthquake occurred. This mound is about three metres high, extending from beneath the delta of the Indus in an easterly direction roughly parallel to the coast. It can be traced over a distance of about 80 km. and is referred to locally as the "Allah Bund" or "Mound of God". Measurements by the Geological Survey of India have shown that generally to the north of the mound the ground was uplifted, and to the south of the mound it subsided.

Almost all large earthquakes have produced extensive fissuring of the ground. The fissures do not extend over great distances like the main faults, and sometimes run in all directions. Fig. 7 shows wide zig-zag fissures along the old course of the Te Awa river which were caused by the New Zealand earthquake. The fissures are, at times, several kilometres in length, and the width varies from a few centimetres to several metres; they may remain open after the shock, or may open and close up again in quick succession. Reports of people and animals having been engulfed in fissures are common; four examples from different parts of the world may be quoted.

(i) During the convulsions of 1692, which destroyed Port Royal in the West Indies, it is said that many fissures appeared and closed up almost at once. In some of these, people were entirely swallowed up and buried.

(ii) When the city of Lisbon was destroyed on 1st November, 1755, there were three great earthquakes originating at 9.40, 10.0 and noon, Lisbon time. The first of these shocks overthrew the greater part of the city and killed thousands of people. It is reported [1] that "Many survivors in Lisbon

[1] Davison, *Great Earthquakes*, p. 5.

fled to a quay, newly and strongly built. With, or about the time of, the second great earthquake, this quay sank, with all the people on it, into a fissure, and no trace of quay or people was seen again."

(iii) The earthquake of 18th July, 1880, in the Philippines caused many fissures to be formed and in some places they were so numerous that the ground appeared to be broken up into steps. Into one such fissure a boat is said to have disappeared, and into another a child; subsequently the body of the child was found a short distance beneath the surface.

(iv) It is recorded that at the time of the Riobamba earthquake in Ecuador on 4th February, 1797, not only were men engulfed, but animals, like mules, also sank into the fissures which were formed.

The Japanese people have believed for many years that there is a risk of being trapped in the cracks, and have a saying that at the time of a large earthquake persons must run to a bamboo grove. This idea originated from a popular belief that the interlacing roots of the bamboo prevent the opening and closing of the ground; this belief is entirely unfounded, for the fissures extend to such depths that their occurrence could not possibly be prevented by roots near the surface.

A. Imamura, in his treatise on *Theoretical and Applied Seismology*, has expressed doubts about the authenticity of the reports of men and animals being swallowed up, since there is no record of such happenings in Japan; he also maintains that no examples are recorded in other parts of the world during the nineteenth and twentieth centuries. This statement is incorrect, for he has neglected one of the occurrences mentioned above, and, in addition, there is another example from the Californian earthquake of 1906. In the Report of that earthquake, volume i, page 72, it is stated that " Mention may be made of the fact that at the Shafter ranch a fault crevice was momentarily so wide as to admit a cow, which fell in head first and was thus

entombed. The closure which immediately followed left only the tail visible."

(i) On some occasions water and other materials such as may be ejected from the fissures; these discharges may continue for several hours after the earthquake. Water and mud were discharged from fissures formed by the Cachar earthquake of 10th January, 1869. The first discharges of dry mud or sand were mistaken for smoke or steam; the water was foul and slightly hotter than the surface water at the time; the sulphurous smell was nothing more than that arising from stirring up the mud at the bottom of a stagnant pool which had lain undisturbed for some time. At the time of the Jamaica earthquake of 1692 men who had fallen into crevices were in some cases thrown out again by issuing water. It was even believed that the sulphurous fumes emitted during this earthquake were powerful enough to cause a general sickness which swept away about 3,000 people.

When the ground on hillsides has been badly fissured large masses of earth may break away and form landslides; large wooded areas from the mountains are frequently carried down into the valleys, leaving the higher land bare of vegetation. Landslides were numerous and large for the Mino-Owari earthquake of 1891, for the Assam earthquake of 1897, and for the Californian earthquake of 1906. In many cases the actual landslides do not occur until some time after the earthquake. An example in Fig. 8 depicts the results of a landslide which occurred in 1907 after much rain had fallen on the ground weakened by the Californian earthquake of the previous year.

It has frequently been stated that during an earthquake waves can be seen travelling along the ground. Sometimes the observers have endeavoured to estimate the sizes and speeds of these waves, but most of the reports are vague, likening the motion to that of sea-waves. Dr. Davison has given reports of the observations of these waves for several great earthquakes; the occasions include the Lisbon earth-

quake of 1755, the New Madrid earthquake of 1811, the Valparaiso earthquake of 1822, the Assam earthquake of 1897, the Alaska earthquake of 1899, and the Californian earthquake of 1906. R. D. Oldham estimated that for the Assam earthquake the average length of the waves was about thirty feet, and that their height was about a foot; for the Californian earthquake we find estimates of as much as two to three feet for the height of the waves. In spite of these, and similar observations for many other earthquakes, it has been suggested that the observers who reported the phenomena had been so disturbed by the shaking movements of the earthquake that they imagined they saw the waves. Some observations made by J. A. Anderson in the Pasadena laboratory during the San Jacinto earthquake on 21st April, 1918, support this suggestion of subjective rather than objective effects. It appeared to Anderson, as he moved across the building, that the concrete floor was thrown into waves of height not less than four to six inches from trough to crest and of wave-length six to ten feet. The waves, if genuine, would have broken the floor in many places but no signs of cracking could be found after the shock, and even relatively unstable objects about the laboratory had not been overthrown. It may be added that instrumental records lend no support to the idea that there should be visible waves from an earthquake.

Disturbances in Lakes, Rivers, Springs, etc.

It has often been observed that, at the time of large earthquakes, lakes have been thrown into violent agitation, or that there have been temporary changes in the level of the water. Some remarkable example of these disturbances are to be found in the records of the great Lisbon earthquake. There are reports of the shock having been felt in Spain, Portugal, northern Italy, the South of France and Germany, northern Africa, Madeira, and other Atlantic islands. In many regions further distant, as, for instance, Great Britain, Holland, Scandinavia, and North America,

although the records are numerous, the only phenomena which were particularly observed were the slow oscillations of the waters in lakes, ponds, canals, etc. In some instances the observers especially remarked that no ground motion could be felt. These oscillations were noticed in many parts of Britain, the waters at some places having risen and fallen through a range of about a metre.

There are a very large number of other earthquakes which have produced similar effects. The disturbance in the Idu Peninsula of Japan on 26th November, 1930, provides a more recent example. On that occasion oscillations of considerable amplitude were noted on Lake Asino-ho. The disturbances of the water are caused by the slow movements of the ground underneath, and may be likened to the slopping backwards and forwards of the water in a basin when the latter is moved.

Just as lakes have been affected, so also have there been sudden disturbances in rivers. Sometimes they have overflowed their banks, and at other times they have been suddenly dried up. In certain cases the reasons for the effects in the rivers are apparent from the topographic changes due to the earthquake. For instance, at the time of the Zenkoji earthquake in Japan in 1847 the Shinano-gawa became partly dry in consequence of the large masses of earth which had been shaken down from overhanging cliffs damming a portion of its course, and thus forming, first lakes, and subsequently new watercourses.

The effects of earthquakes upon springs are varied. Old ones may dry up and new ones may be formed ; the purity and temperature of the waters may change. Varied examples of these changes are to be found in the observations of the Californian earthquakes. It has also been noted that earthquakes may cause fluctuations in the levels of the water in deep wells, located in regions at considerable distances from the epicentres. The level of the water in a well is sometimes raised by the earthquake and subsequently recedes very slowly to the original position.

Disturbances in the Ocean

Although submarine earthquakes are common the observations of the phenomena which accompany them are very incomplete. Occasionally, these earthquakes are noticed, if ships happen to be in the vicinity, and sometimes their destructive powers are indicated by breakages in submarine cables, but the majority of the shocks can only be detected from the records of instruments. The effects are analogous to those for shocks under the land; disturbances are felt on board of ships, sounds are sometimes heard, and the topography of the ocean floors may be changed.

That even a small earthquake can be noticed on ships is shown from the observations of the shock under the North Sea on 7th June, 1931. This shock was felt on several ships in the vicinity. The navigator of a motor boat, about 40 km. south-east of Flamborough Head, reported that a sound like that of a distant lightship gun was first heard, followed by a series of underwater explosions, like those of depth-charges 5 to 10 km. away. The sea was then calm, but fifteen or twenty minutes later a heavy swell developed and became very confused appearing to roll from all directions.

There are numerous reports of submarine cables being damaged or broken by earthquakes, especially for the cables beneath the Straits of Messina and between the Japanese Islands. In 1888 three cables connecting Australia with Java fractured simultaneously, and, on the supposition that this sudden isolation indicated an act of war, the Australian naval and military reserves were called out. The development of wireless telegraphy and telephony has overcome this isolation, but even now communications may be very badly disorganized by a submarine earthquake. The earthquake beneath the North Atlantic near the Grand Banks of Newfoundland on 18th November, 1929, caused much damage to cables in that region; the breakages occurred over

an area extending several hundred kilometres from the epicentre. Some of the first Milne seismographs were installed in various parts of the world with a view to explaining the reasons for interruptions of cable communications. It is stated by Milne in the British Association Report for 1913, page 41, that "Directly it was shown that certain sub-oceanic disturbances had interrupted cables, Colonies desirous of knowing the cause of these sudden isolations from the rest of the world set up seismographs. This was the commencement of the British Association co-operation of seismological stations."

In many cases submarine earthquakes give rise to great sea-waves, which approach the coast-line as a long unbroken swell with the height increasing as the water gets shallower. The waves travel inwards at a speed of several metres per second and sweep over low-lying ground near the coasts. If the inundated regions are inhabited these waves may cause terrible loss of life and extensive damage. These sea-waves are called "tunamis", meaning long waves in harbour, from the Japanese *tu*, a port, and *nami*, a long wave. Over the open sea the amplitude is rarely more than one or two metres and the period of the waves is so long that they are not noticed.

Much of the great destruction which occurred at the time of the great Lisbon earthquake (1755) was due to a series of great sea-waves, about ten to twenty metres higher than the highest tide, which swamped the town. These came in about an hour after the town had been shattered by the motion of the ground. The first motion in the waters was their withdrawal, which was sufficient completely to uncover the bar at the mouth of the Tagus. At Cadiz, the first wave, which was the greatest, is said to have been nearly twenty metres in height. Fortunately the devastating effect which this would have produced was partially warded off by cliffs. The sea-waves from this earthquake swept over many parts of Portugal, Spain and northern Africa; about two hours after the shock the waves reached Funchal

in Madeira, and some three hours later they were observed around the coasts of the British Isles; the waves travelled right across the Atlantic, and were observed at several places in the West Indies, having passed over a distance of about 5,700 km. in ten hours.

Among the most terrible submarine earthquakes are those near the Sanriku coast of Japan on 15th June, 1896, and 2nd March, 1933. In each case the destruction was almost entirely caused by the sea-waves which inundated the coastal regions. The earlier happened on the evening of a public holiday, and the tunami, with waves as much as 24 metres in height, swept over about 150 km. of the coast-line, drowning almost everyone in many towns and villages, and reducing the buildings to ruins. The magnitude of the disaster is indicated from Imamura's estimate that 27,122 people lost their lives, 9,247 were injured, 10,617 houses were swept away, and 2,456 houses were partially demolished. The sea-waves travelled across the Pacific reaching Honolulu, 5,820 km. away, in 7¾ hours, and the North American coast near San Francisco, 8,000 km. away, in 10½ hours. Out at sea the waves were so long and flat that fishermen did not observe them, but when they put back in the morning they came upon wreckage and floating bodies and found their villages reduced to heaps of sodden débris. At one place four steamers had been carried inland, and nearly two hundred vessels of various descriptions lined the foothills. The sea-waves of the 1933 tunami did not rise as high in some regions as those for the earlier tunami on the Sanriku coast, but the damage occasioned by the two disasters was about the same. Fig. 9 [1] illustrates the havoc wrought by the 1933 tunami, showing the ruins of what had, before the disaster, been Japanese villages; it will be seen from these photographs that most of the houses had been smashed to pieces by the waves.

[1] These photographs are taken from the Report published by the Earthquake Research Institute of Tokyo.

Although we know that some sea-waves have been produced by submarine volcanic eruptions, and others possibly by submarine landslips, in these cases their origin was certainly seismic. They came from the Tuscarora Deep, a district which is well known as the birthplace of many severe shakings, and the seismic waves from the preceding shocks were recorded by instruments at the seismological observatories in all parts of the world. A whale or a submarine in deep water may move from point to point and not betray its presence by a ripple on the surface, but if the size of the moving mass is at all comparable with the depth of the water, this is no longer the case. To explain the waves of 1896 and 1933, which originated in water reaching to a depth of 4,600 fathoms, all that is required is a sudden displacement of material equal in volume to that which has been displaced in many of the great earthquakes which have occurred underneath the land.

An example frequently given of a submarine earthquake is that which devastated Iquique, Chile, on 9th May, 1877. The first motion which was observed in the sea was that it silently drew back for over 60 metres, after which it rose as a wave nearly two metres high. At some places the water came in as waves from five to twenty-five metres in height. The waves were observed in Japan where they continued for nearly a whole day ; the period and amplitude of the rise and fall were variable, usually the waves quickly reached a maximum and then died out gradually. As observed on a self-recording tide gauge at San Francisco, the disturbance lasted for about four days. A diagram of this is given in Fig. 10. In its general appearance this diagram is very similar to the records of other earthquake sea-waves. The large waves represent the usual six-hour rise and fall of the tides ; normally these are fairly smooth curves. Superimposed on the large waves are the smaller zig-zag curves of the earthquake disturbance, lasting with greater or less intensity for several days. As these curves are drawn to scale—horizontally for hours, and vertically

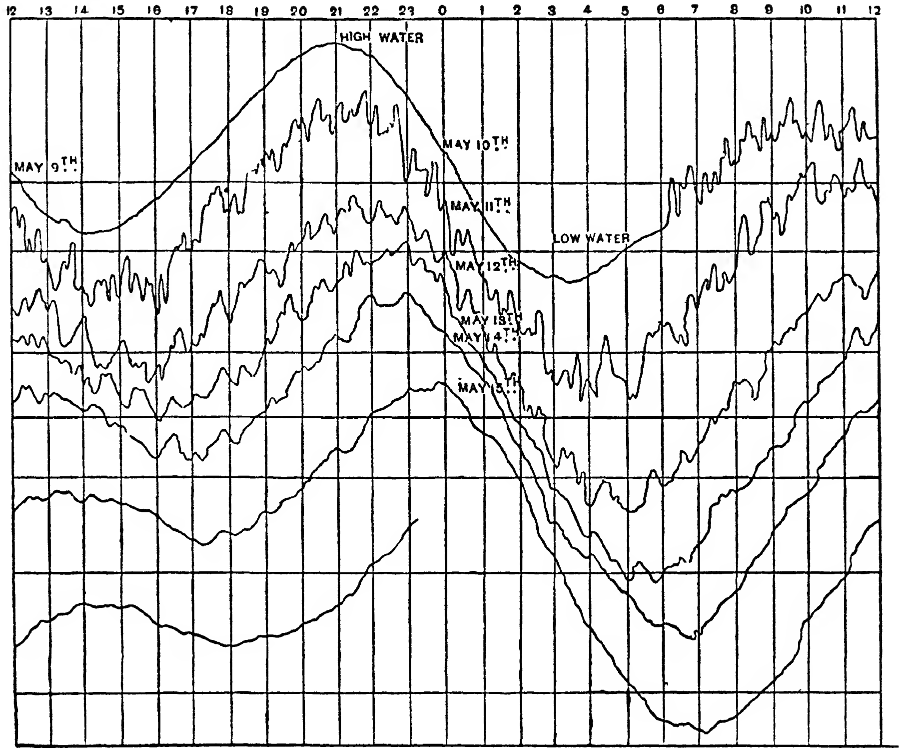


FIG. 10.—Record of tide gauge at Port Point, San Francisco; showing earthquake sea-waves of May, 1877

one fifth inch to the foot, to show the extent of the rise and fall—they will be easily understood.

Sometimes, as in the present example, the first movement in the waters is that of an incoming wave. In many instances, however, this observation may be due to the slow and more gentle phenomena of the previous drawing out of the water, which, on a steep coast or when the water is rough, would be difficult to observe and might pass unnoticed. The waves of the Iquique earthquake were observed around the basin of the Pacific, from New Zealand in the south, to Japan and Kamtchatka in the north.

CHAPTER IV

EARTHQUAKES AND CONSTRUCTION

THE subject of this chapter is, from a practical point of view, one of the most important with which a seismologist has to deal. We cannot prevent the occurrence of earthquakes, and unless we avoid earthquake shaken regions, we have not the means of escaping from them. What we can do, however, is in some degree to protect ourselves. By studying the effects produced by earthquakes upon buildings of different construction and variously situated we are taught how the calamities, which in certain regions of the world are continually repeated, may be mitigated.

The distribution of the damage throughout a large city, which has been stricken by an earthquake, at first sight appears to be absolutely chaotic, but in many cases the results of observations have shown that the damage depends largely upon the nature of the ground in the neighbourhood and upon the type of buildings. The amount of damage does not depend upon the size or speed of the movements so much as upon the acceleration of the ground. The important factor is the suddenness of the motion in stopping or starting, or, more briefly, the jerk. The acceleration of the ground can be calculated from the records of suitable instruments, or estimated from the dimensions of pillars and similar objects which have been overturned. The greatest accelerations of the ground during earthquakes are about half that of gravity ; the maximum acceleration was from 0·4 to 0·5 of gravity for the Mino-Owari earthquake of 1891, the Assam earthquake of 1897, the Tokyo earthquake of 1923, and for the Tango earthquake of 1927.

There are other disastrous earthquakes, however, in which the maximum accelerations were less ; among these are the California and Messina earthquakes with maximum accelerations of about 0·2 of gravity.

Comparisons of the Damage on Stable and Unstable Ground

It has been known for many years that, other things being equal, the damage caused by an earthquake is less for buildings constructed on firm rocky ground than for those on alluvial or swampy ground.

This feature was shown very clearly in the distribution of the damage around San Francisco from the earthquake of 1906. The hills in the district are of firm rock (sandstones, chert, serpentine and shales), which frequently outcrop through a thin layer of soil ; the lower slopes are covered by sand and alluvium, with the thickness of these superficial deposits increasing towards the valleys or the sand-dunes near the coast. The whole of the region was well within the destructive zone of the earthquake, and almost everywhere chimneys were brought down and ceilings and plaster were damaged. There were, however, some small localities in which most of the chimneys withstood the shock, and again there were others where buildings were wrecked, sewers and water-mains were broken, and the surface of the ground was distorted into irregular waves. Generally the regions where the damage was notably small were those on the firm rock, and those which suffered most were on the weaker subsoil.

For the great Japanese earthquake of 1st September, 1923, the damage was much greater in districts situated on unstable ground than in those on more solid formations. It has been estimated that the disturbance in the regions of Tokyo on alluvium was four or five times that in areas covered by tertiary formations or by solid volcanic rock.

The effects of the type of ground upon the damage were

very clearly shown by the St. Lawrence earthquake of 28th February, 1925, which was felt in the eastern parts of Canada and the United States, and cracked the walls of many buildings in the region from Quebec to Tadousac. Structures near the river on alluvial deposits or those on sand-hills were damaged, but those built on rock were not. In Quebec, buildings on the weak ground near the river were damaged, while the shock was not felt in many places on the cliffs.

The earthquake of 11th July, 1927, showed a similar relation between the severity of the shock and the characteristics of the ground. This earthquake was felt over a large part of Palestine and caused much damage in a number of towns. In Nablus, situated on either side of a valley 50 km. north of Jerusalem, the damage was slight on the rocky slopes of the northern and southern sides of the town, and very severe in the central region which is built on alluvium.

Numerous other examples could be given for which this relationship holds. There are, however, records of a number of earthquakes for which buildings on rock suffered the greater damage. In the New Zealand earthquake of 2nd February, 1931, the damage on Seinde Island to buildings on limestone was notably greater than that to similar buildings around Hastings on alluvium. Again, in the Italian earthquake of 16th July, 1930, the greatest destruction and loss of life occurred in regions on rock.

The greater damage would naturally be expected on the alluvium. The movements produced there, for a given amount of energy in the shock, are much greater than those on rock, and the resistance to faulting or fissuring is much less. In view of the contradictory results obtained from different earthquakes, it seems that the damage is not always affected by the subsoil as much as by other factors, such as differences in the materials and methods of construction, or the proximity to the epicentre.

Prevention of Damage to Buildings

The picture of the city of Napier (Fig. 1) after the 1931 earthquake, shows that some buildings were much more severely damaged than others in the immediate vicinity. The susceptibility of a building to damage is influenced by its height and rigidity. A perfectly rigid building carried on good deep foundations would undergo the same movements as the ground. In practice, however, all structures are more or less flexible, and tend to oscillate after they have been displaced. Hence, while the movements at the bottom of a building during an earthquake are the same as those of the ground, those on the upper floors may be larger. This fact was brought out recently when the Belgian earthquake of 11th June, 1938, was felt in London. The shock was noticed by people on the upper floors of tall buildings, and not by those on the lower floors.

For the buildings in a country subject to violent earthquakes it is essential to use materials of the best quality and to adopt as simple a plan as possible; heavy copings or other additions at the top of tall buildings should be avoided. Ordinary methods of construction with brick walls may be used for buildings of two or three stories, but for higher structures reinforced concrete is the most suitable material.

In nearly all countries where there is legislation respecting the character of buildings which may be erected in seismic districts, attention is paid to the character of the foundations that are to be employed. If the ground is soft a thick platform of reinforced concrete should be laid over the whole of the area to be covered by the building. Experience has shown that a building standing upon a continuous solid foundation suffers less from vibration.

It has been found that the movements experienced in pits several metres below the ground are less than those upon the neighbouring surface; it may therefore be inferred that a building rising freely from a deep foundation, as in the

case of a house with an open area and a basement, will be subject to less movement than a building rising directly from the surface. This was demonstrated about fifty years ago from the behaviour of some large buildings in Tokyo forming part of the Imperial University. These buildings successfully resisted the effects of several very heavy shakings, while neighbouring buildings, equally strong so far as masonry is concerned but rising directly from the ground, were cracked or partly demolished.

Lightness combined with strength is essential for walls to withstand severe earthquakes. The height to which walls may be taken depends upon their thickness, the material with which they are constructed, the number and disposition of windows and other apertures, the weight of the roof, etc. As the building sways during an earthquake the walls are strained, and are particularly liable to crack if there are any lines of weakness (Fig. 11). Walls, shaken crosswise with sufficient violence to fracture them, generally crack at the bottom. If the shaking is directed along the length of the wall the cracking most frequently occurs in the higher parts just below the roof. The plaster on walls and to a lesser extent on ceilings is liable to crack or break off in large pieces; the damage to the plaster is greatest on the lower floors.

Roof trusses must be light and rigid, and should be carried on wall plates; they must be kept as far as possible from points of weakness such as may be formed by openings in the walls. The roof itself should not be too steeply pitched; it is a common experience that steep roofs have lost their coverings of tiles or slates, whilst the coverings of neighbouring buildings with flatter roofs have not been disturbed. On account of their lighter weight, slates are preferable to tiles for use in countries subject to severe earthquakes.

The chimneys are the most vulnerable part of a house to earthquake damage, and if they collapse may crash through the roof and several floors. It often happens that after an

earthquake of moderate intensity almost every house in a town, although it has not suffered any other appreciable damage, has had its chimneys shaken down or rotated. The point at which the chimneys yield is almost invariably where they leave the roof. To minimize the risk of damage chimneys should be as short and thick as possible. They should be constructed, if possible, of reinforced concrete or of iron ; if brickwork is used some measure of protection may be obtained by strengthening the corners with angle irons.

As a result of investigations of the damage to buildings from great earthquakes of recent years, such as those in San Francisco (1906) and in Tokyo (1923), it appears that even large commercial buildings have withstood some of the most severe shocks. On each of the occasions mentioned above, by far the greater part of the damage was caused by the fires which followed the earthquakes. The fires in San Francisco did not reach the busiest part of the city until several hours after the earthquake, and photographs were taken in the meantime which show that many of the large buildings were practically undamaged by the shock. Most of the tall buildings were still standing after the earthquake, and in many cases the cornices, parapets, and even chimneys, were apparently intact. Although solidly built on frameworks of steel girders, these buildings generally suffered extensively from the conflagration which could not be extinguished until several days after the earthquake. The photograph in Fig. 12 shows how in Tokyo many buildings withstood the shock of the earthquake but were destroyed by the fires.

The earthquakes of San Francisco, Tokyo and Hawke's Bay, emphasize the truth of the Japanese saying " After a great earthquake there comes fire." There is little wonder that fires break out in many parts of a city which has been subjected to a severe shock, for nearly every damaged house or chimney may start a separate outbreak. If the shock has destroyed the city water supplies a general conflagration generally follows. Most of the damage in San Francisco

might have been prevented if the water supplies had not failed. Fig. 13 shows examples of the damage to a 30-inch main, of the Spring Valley Water Company, which conveyed water from Pilarcitos Lake to the city. The main was of wrought iron buried about a metre below the surface, and being lain across the great San Andreas fault, which was the seat of the earthquake, was fractured or telescoped in several places ; in one region it collapsed completely for a distance of several metres. As a safeguard against a repetition of the 1906 calamity the ordinary water supplies of San Francisco have been augmented, and a vast auxiliary system has been constructed. This system has separate reservoirs and is fed through mains which were specially designed to withstand earthquake damage. In the event of a breakdown in the supply from the reservoirs water can be pumped into these mains from the harbour.

Many lessons have been learned from the observations which have been made in recent years of the damage caused by large earthquakes to buildings of different types. As a result of these observations it is found that properly designed and constructed buildings, whether large or small, can survive these shocks with only a comparatively slight amount of damage. The older buildings in all countries are gradually being replaced, and with the new structures built on more scientific lines, we are justified in hoping that in the future there will be a great reduction in the loss of life and material damage due to earthquakes.

A tall factory chimney, which is broken by the first impulse from an earthquake, generally snaps off near the bottom, but if the chimney is set swinging and then breaks the fracture tends to occur higher up. Sometimes although the chimney may be broken the oscillations may not be large enough to dislodge the upper part which has been detached. The use of steel or of reinforced concrete for these structures is now enforced in many seismic regions, where the regulations governing the construction of large buildings are generally very stringent.

The damage to bridges is usually greatest near the abutments, but often where the spans are supported by piers these have been fractured or cracked. Bridges with each of the piers built in the form of an arch are common; the example shown in Fig. 14 was a railway bridge over the river Kiso in central Japan. The fracture on the right of the first pier in the picture was caused by the Mino-Owari earthquake of 1891. The sides of each arch were carried by separate circular curbs set in the bed of the river, and it is possible that relative motion between these curbs was a factor in causing the fracture; the effects of this motion would be increased owing to the line of weakness which extends across the arch just where the cracking occurred. It has now been realized that arched piers are unsuitable for use in seismic regions, and they have been replaced by solid piers supported by continuous foundations.

The resistance of a solid pier to earthquake shocks depends upon the strength at the bottom. For this reason tapered piers of the type shown in Fig. 15 withstand the shocks just as well as those of uniform cross-section, and are more economical to construct. The amount of taper permissible can be calculated from the properties of the materials and the forces which the piers are designed to withstand. In some cases a stronger cement has been used towards the bottom of the piers with a view to obtaining greater security.

Earthquake Insurance

The insurance of property against earthquake damage is a subject which, owing to the magnitude of the possible risks, must be studied very carefully by those transacting business of this kind. As examples of the amounts which may be involved we recall the rough estimates of the total value of the property damaged in some recent disasters. The figure given for the Californian earthquake of 1906 is about a hundred million pounds, that for the Italian (Messina) earthquake of 1908 is twenty-two millions, and for

the great Japanese earthquake of 1923 it reached the colossal sum of 550 millions. Each of the larger of these amounts includes the damage from the accompanying fires as well as that directly caused by the shocks; the damage caused by the fires on each of these occasions was many times that due to the earthquakes. The fire-insurance policies in San Francisco in 1906 did not exclude the risk from fires caused by earthquakes, but the resources of the companies involved were insufficient to meet the claims in full. In countries liable to severe earthquakes the policy conditions have since been amended so that the ordinary fire-policies do not cover risks resulting from earthquakes. The companies were safeguarded by these conditions on the occasion of the 1923 earthquake, but, with the assistance of the Japanese Government, voluntary grants, known as "sympathy payments" were made of a tenth of the damage. These payments were made as an act of grace and were conditional on the recipients undertaking to make no further claims for compensation.

The demand for earthquake insurance fluctuates—the news of a great earthquake in any part of the world makes the public apprehensive and there is a temporary increase in the amount of business, but in time the alarm subsides and the amount of insurance decreases. Buildings in any part of the world can be insured against damage by earthquakes, but it is usually a matter of some difficulty to fix the rates at which the insurance can be accepted. In deciding what these rates should be it is necessary to provide adequate cover for the risks involved and to allow a fair margin for contingencies and profits. Among the factors to be considered are:

(i) The amount of business to be transacted and the area over which the risk is distributed.
(ii) The seismic character of the regions concerned.
(iii) Local peculiarities such as the type of ground and distances from known faults if insurance is only being affected for buildings in one city or throughout a limited region.
(iv) The type of buildings to be insured.

In connexion with (i) we note that, even for a large earthquake, the damage is confined to a region which generally does not extend more than ten or twenty miles from the epicentre of the earthquake; consequently if the insurances are distributed over a large area, the risk is less than for the same amount of property in a single city, where all the buildings might be destroyed by one earthquake. Although it is impossible to predict earthquakes, the statistics for past disasters can be utilized to obtain the average frequencies with which they occur in particular regions. The catalogues of earthquakes and maps of epicentres referred to later in Chapter IX may be used for this purpose. The historical catalogues are particularly valuable for they provide a means of estimating the average interval between the successive destructive earthquakes in many regions. With regard to (iv) it will be recalled that the essential features for buildings designed to withstand earthquake damage are simplicity of design combined with adequate strength, and first-class materials and workmanship. In assessing the risk of damage to buildings of different types it is convenient to start with a factor termed the "expected loss ratio", which represents the average amount of damage caused by a great earthquake, expressed as a percentage of the sound value of the properties of that type. Naturally for some buildings of each type the damage may be much greater than the average, whilst for many others it is less. The specifications of buildings and the loss ratios given [1] by A. C. Chick, an engineer of the Manufacturers Mutual Fire Insurance Company, U.S.A., are set out in the following table.

[1] Bulletin, Seismological Society of America. Vol. 24, 1934, p. 388.

EXPECTED LOSS RATIO FOR VARIOUS TYPES OF CONSTRUCTION

Class	*Description*	*Expected loss ratio Percentage of sound value*
I.	Steel-framed, reinforced concrete buildings specifically designed to resist earthquake forces (not over 100 feet high). Wood-frame dwellings set on good foundation walls—not on posts, piers, or "cripples" (not over two and one-half stories high).	2–4
II.	Steel-framed, not specifically designed to resist earthquake forces, but having good wind bracing, with curtain walls of reinforced concrete, or brick laid in good cement mortar, or with walls of corrugated iron or asbestos (not over 100 feet high).	4–6
III.	Well-built reinforced concrete buildings without riveted or welded steel frame, with curtain walls of reinforced concrete, or of brick laid in good cement mortar (not over four stories high).	5–7
IV.	Steel-framed buildings with questionable wind bracing with walls of brick laid in good cement mortar, in which the loads are carried by the steel frame, floors of plank or timber or of joisted construction (not over 100 feet high). Brick residences, mercantile and office buildings of excellent design, with walls of brick laid in good cement mortar (not over three stories high).	6–8
V.	Ordinary, well-built brick bearing-wall factory buildings, with strong wooden floors and roof supported by interior columns of wood or steel and by outside walls of brick laid in good cement mortar, with little or no expensive interior finish or parapet walls or ceilings (not over four stories high).	6–10
VI.	The same as Class V, but having interior partitions of tile, brick, or plaster. General average of commercial buildings with reinforced concrete frames and columns (no steel frame), with curtain walls and partitions of hollow tile and with large window openings in the lower story.	10–20

Class	Description	*Expected loss ratio* *Percentage of sound value*
VII.	Brick-veneered, wood-frame, or concrete-framed residences, mercantile and office buildings, or stucco exterior on wood lath, or with hollow tile partitions.	20–30
VIII.	Buildings of doubtful quality of design and construction, with uncertain wall ties, unanchored parapets, ornate trim, uncertain quality of mortar, etc.	20–50
IX.	Concrete block, hollow-tile or adobe buildings.	50–100

The figures given in the table are the average loss ratios to be expected for structures on firm, natural ground. If the foundations rest on mobile ground or soft alluvium the ratios must be increased, and if they are on bedrock the ratios may be reduced. On weak formations the damage may be as great as ten times the average values.

Chapter V

SEISMOGRAPHS

The object of this chapter is to give a general description of the instruments used for the registration of earthquakes. These instruments, which are called seismographs, are affected by vibrations of the ground, and most of the types now in use are so sensitive that records can be obtained of the tremors propagated from earthquakes on the other side of the world. Many of the early seismographs have become obsolete, and are not described here; information regarding these types, and the still more ancient seismoscopes and seismometers can be obtained from the books by Milne and other contemporary writers.

The movements of the ground to be recorded by seismographs are travelling in various directions when they reach the instruments. The motion may be regarded as composed of the component displacements along three axes at right angles to each other; the directions usually chosen for these axes are to the north, to the east, and vertically upwards. The equipment for completely recording the earth displacements is therefore two seismographs for the horizontal components and one for the vertical. It is much more difficult to obtain satisfactory records of the motion in the vertical than in the horizontal directions and many of the seismological observatories have no vertical seismograph.

General Principles of Seismograph Design

An instrument to measure the movements of the ground is placed either directly on the ground or on a stone pillar

resting thereon, and when the earth moves the whole of the instrument is carried with it. It is necessary that the instrument should contain some system which does not follow the earth movement. A simple pendulum could be used for this purpose ; the bob would tend to remain at rest whilst the support would follow the earth movement, and the earth-waves would set up relative movement between the framework and the bob. With such an arrangement, however, the relative motion caused by a distant earthquake would be very small, and various modifications have been made to increase the sensitivity. At first experiments were made with longer pendulums, but later it was realized that the more convenient method of overcoming the difficulty is to reduce the force which tends to keep the pendulum to its original position. Accordingly the pendulums used are of special types in which the effective control is less than that of the simple pendulum ; the weaker the control the better, provided that the pendulum remains stable and returns to its original position after being displaced. The pendulums incorporated in some types of horizontal and vertical seismographs are illustrated in Figs. 16 and 17 respectively.

An inverted pendulum is shown in Fig. 16 (*a*). The mass carried by an upright rod is hinged to the base through two flat springs at right angles to each other, and is free to move in any horizontal direction. The instability of this arrangement can be overcome by connecting the mass to the framework by small springs.

In the ordinary horizontal pendulum the mass is carried by an arm attached to the framework and free to move about a nearly vertical axis. Such a pendulum would be in neutral equilibrium if the axis about which it rotates were exactly vertical, and it is made stable by tilting the axis slightly towards the centre of gravity. In practice, i, the inclination of the axis to the vertical, is very small. The system is equivalent to a compound pendulum for which the effective value of the acceleration due to gravity is reduced from g to $g \sin i$. If the inclination is reduced the control diminishes

and the free period of the pendulum is increased. In the Milne type of seismograph, Fig. 16 (*b*), the suspension is by a single wire to the arm carrying the mass, and the end of this arm nearer the axis has a pivot bearing. For his horizontal pendulums Galitzin used the Zöllner suspension (*c*) in which

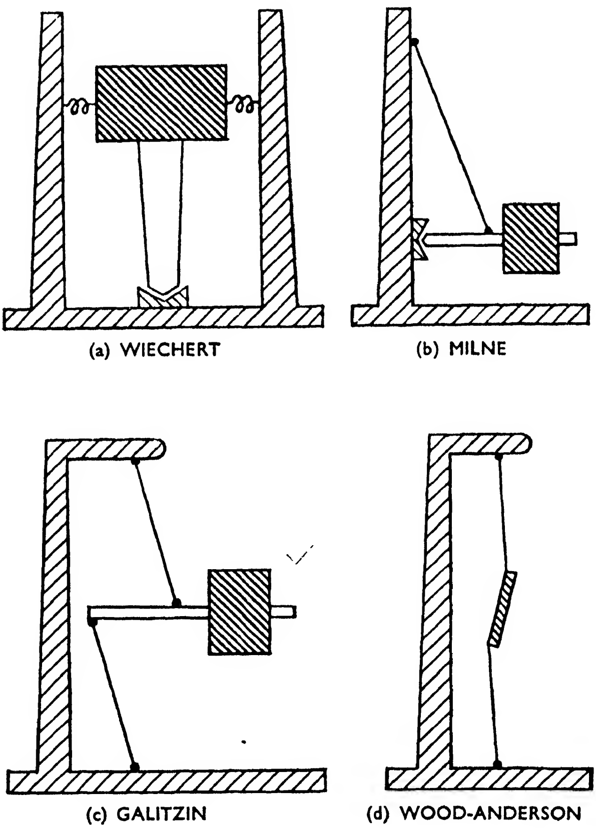


FIG. 16.—Types of suspension of horizontal seismographs

the rod carrying the weight is supported from the framework by two wires; the wires are arranged so that both are pulled taut by the weight. In the Wood-Anderson seismograph a very small mass is attached eccentrically to a fine wire; the wire is distorted slightly by the mass,

Fig. 16 (*d*), and the suspension is really on the same principle as that of the Galitzin instrument. It will be noticed that the horizontal pendulums are affected chiefly by movements in a direction perpendicular to the plane of the

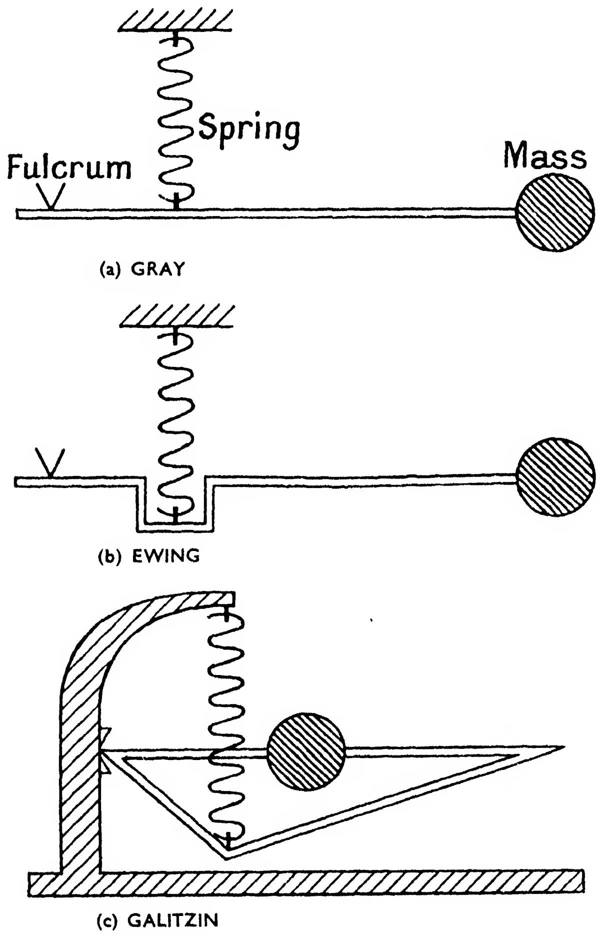


FIG. 17.—Types of suspension of vertical seismographs

diagrams ; any movements in other directions are very small and need not be taken into account.

During the nineteenth century many attempts were made to devise an instrument for measuring the vertical move-

ments of the ground. In some of these the mass was carried at the end of a strong horizontal spring projecting from a wall, in some it was suspended from a coiled spring, and in others it floated in a vessel of liquid. None of these instruments were satisfactory on account of the difficulty of obtaining a sufficiently long free period. The problem was solved in 1880 by T. Gray, who constructed an instrument in which the mass is fixed to one end of a lever with the spring attached, as shown in Fig. 17 (*a*), between the fulcrum and the mass. If l and l' are the lengths of the longer and shorter arms of the lever respectively, an extension of the spring through a distance h moves the mass through a distance hl/l' ; hence in comparison with the free period for the mass suspended directly from the spring the period is lengthened in the ratio $1 : \sqrt{l/l'}$. To increase the stability of the instrument Gray attached to the outer end of the bar a hermetically sealed tube containing mercury, which when the bar was depressed ran outwards and increased the load in such a manner as to compensate for the decreased leverage. Ewing, in the following year, devised another method of compensation, by attaching the spring below the axis of the lever, Fig. 17 (*b*) ; with this arrangement when the spring lengthens, or when the moment of the mass is reduced, the point of attachment moves towards the fulcrum, and *vice versa* when the spring shortens. These principles have been incorporated in the design of the Galitzin vertical seismograph, Fig. 17 (*c*). In this instrument the mass is fitted into a triangular support which is hinged to the main framework by crossed springs and carried by the coiled spring.

When a pendulum is disturbed it oscillates with its natural free period, and the oscillations might be large enough to mask any earth movements after the first in an earthquake record. A record of this sort would be of little value, and the free motion of the pendulum must be suppressed ; in other words the motion of the pendulum must be damped. The damping is obtained by attaching to the pendulum a

mechanical or magnetic system which restrains the free movement. The methods adopted for damping various kinds of seismographs are described later. The amount of damping to be applied requires careful consideration ; if it is not enough the free oscillations die down very slowly, if it is too great the pendulum is sluggish, and, when displaced, only returns very slowly towards the undisturbed position.

The effects upon the pendulum movement of different amounts of damping are illustrated in Fig. 18. The first diagram (*a*) shows the ordinary simple harmonic oscillations of an undamped pendulum. Fig. (*b*) represents the motion with an amount of damping which is not sufficient to prevent the pendulum from oscillating, and the pendulum is said to be underdamped. The amplitudes of the oscillations diminish with time, and the ratio of successive amplitudes is termed the damping ratio. Owing to the retardation of the motion the period of the oscillations is greater than that of the pendulum when swinging freely. As the damping is increased the amount by which the pendulum overshoots the zero after its first excursion gets less and less ; eventually a condition is reached in which the zero is not crossed at all. Theoretically the pendulum returns nearer and nearer to the original position but never quite reaches it. The case illustrated in (*c*) is the one in which the free motion is suppressed in the shortest time possible ; the pendulum is critically damped, and its motion is deadbeat or aperiodic. If the damping is greater than that for aperiodic motion the recovery towards the zero is slower as shown in (*d*). The pendulum is then said to be overdamped.

The horizontal pendulums respond to slow tilting of the ground as well as to the displacement, and for sensitive instruments the movements due to tilting may be troublesome. A large drift of the pendulum may be caused by even slight tilts such as arise from the unequal heating of different sides of a building or in some districts from the tides.

About 40 years ago, when the earth movements of long periods were believed to be the most important features of earthquake records, it was thought that the high magnifica-

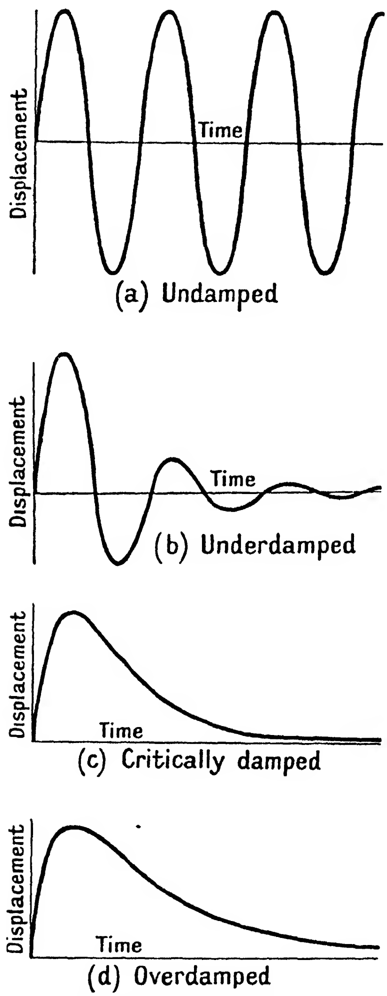


FIG. 18.—Pendulum motion for various conditions of damping

tion needed for recording could best be obtained by lengthening the pendulum period. The period is generally increased by bringing the axis of rotation nearer to the vertical, but

if the inclination is too small the pendulum becomes unstable; also, with a pendulum of very long period, the operation of the seismograph is very badly upset by the slow tilting of the ground. Hence the periods used are not longer than about 12 seconds, except for special instruments which are not affected by the tilting.

The special pendulum serves to pick up the earth-waves, but these movements are very small and the complete seismograph must also include means whereby the pendulum motion can be magnified and recorded. The theory of the operation of seismographs, and the magnification given by instruments of different types, has been worked out mathematically. The results obtained from the theory are of great importance in showing how the response of a seismograph depends on the kind of earth movement to be recorded, and on the characteristics of the instrument in use.

The ratio of the amplitudes of the displacements shown in the records to those of the corresponding earth movements is termed the "magnification" of the seismograph, and is usually represented by the letter V from the German *Vergrösserung*. The magnification for very rapid movements depends upon the dimensions of the instruments. If the mass is moved through a small distance x, the angular deflexion of the pendulum is given by $\theta = x/l$ where l is the length of the simple pendulum having the same free period as the seismograph. The ratio of y, the displacement on the record, to θ depends upon L, the length of the recording levers or of the light beam according to the method of registration; for small deflexions the ratio is constant and we may write $y = L\theta$. Thus the magnification is L/l; this is referred to as the "static" magnification and represented as V_0.

If the earth movements affecting the seismograph are periodic waves of simple harmonic type, the pendulum follows the oscillations of the ground and the recorded movements are also simple harmonic waves. In this case

the magnification depends on the damping and on the ratio of the period of the earth-waves to the free period of the pendulum, as well as on static value. The formula by which the different factors are related is

$$V = V_0 \{(u^2 - 1)^2 + Du^2\}^{-\frac{1}{2}}$$

where D is a constant which can be determined from the damping ratio, and u is the ratio of the period of the earth-

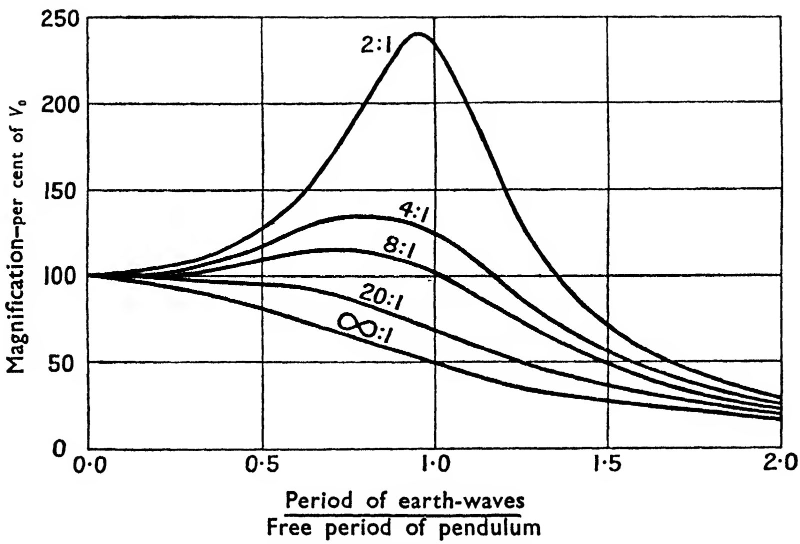


FIG. 19.—Seismograph magnifications for waves of different periods

waves to that of the pendulum. From this formula we can calculate, for a prescribed amount of damping, the relative magnifications, V/V_0, which correspond with different values of u. The results obtained from some calculations of this sort are depicted in Fig. 19. The ordinates of the diagram represent the ratio of the periods of earth-waves and pendulum, the abscissæ are the magnifications expressed as percentages of V_0. The waves show the magnifications for pendulums with damping ratios of 2 : 1, 4 : 1, 8 : 1, 20 : 1, and for critical damping when the ratio becomes ∞ : 1.

Whatever the amount of damping the static magnification

is appropriate for very rapid oscillations, and for very slow waves the magnification falls off to zero. Between these limits the magnification depends upon the damping. For well-damped pendulums the magnification diminishes progressively as the period of the earth-waves increases. For pendulums which are badly underdamped the magnification rises to a maximum and then decreases; earth-waves of periods rather less than the free period of the pendulum are therefore unduly prominent in the records obtained from seismographs which are badly underdamped.

The Milne Seismograph

Before considering the modern instruments a description will be given of the Milne Seismograph which is of such great historical interest. The design is shown in Fig. 20. The mass consists of two brass spheres carried transversely on a boom which is pivoted, by means of a quartz cap resting on a steel point, near the base of an iron stand; the supporting tie is a fine brass wire. At the other end the boom carries a light aluminium plate in which there is a fine slit parallel to the length of the boom. The plate and slit move over a second slit in the top of a closed box which contains the photographic paper used for recording; this paper, in the form of a long narrow strip, is passed over a drum driven by clockwork. The light from a very small kerosene flame passes downwards through the upper slit after being reflected from an inclined mirror. The second slit is perpendicular to the first and only a fine point of light passes on to the recording sheet in the box. The slit in the recording box extends on either side beyond the plate carried by the pendulum, and light reaches the photographic paper at the sides as well as beneath the intersection of the slits. The record, when undisturbed, has a fine line in the centre of the sheet with a black band at either side. As the pendulum swings the displacements of the central line are accompanied by broadening of the side bands, and for very

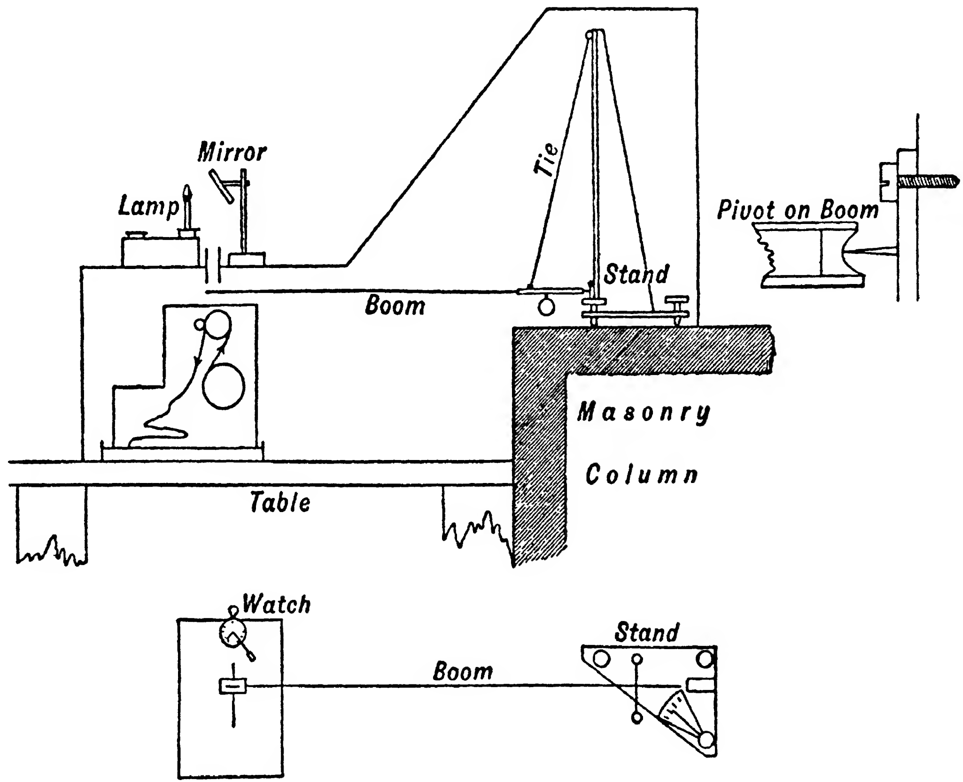


FIG. 20.—Milne seismograph

large oscillations the bands extend right across the sheet. An extension from the minute hand of a watch crosses the slit at hourly intervals and, by eclipsing part of the light, gives a record of the time.

Instruments of this type were selected by the Seismological Investigation Committee of the British Association in 1897 for use in a general seismic survey of the world, and their installation marked the beginning of international co-operation in the study of earthquakes. Kew Observatory was one of the first stations to be equipped, and a Milne seismograph was in operation there from 1898 to 1924. The records obtained from the Kew instrument for five great earthquakes are shown in Fig. 21. The direction of these records is from left to right and each covers an interval of about three hours. The times of the initial movements and of the largest oscillations in the records are as follow:

Earthquake	Times from Kew records (G.M.T.)				
	Commencement			Maximum	
	d.	h.	m.	h.	m.
Alaska. September, 1899	10	21	1·6	22	20
California. April, 1906	18	13	25·7	13 57 to 14 2	
Valparaiso. August, 1906	17	0	33·3	1	50
Messina. December, 1908	28	4	23·6	4 31 to 4 33	
Tokyo. September, 1923	1	3	11·0	3	52

An improved method of recording was introduced in the Milne instruments which were constructed several years after the original type had been introduced. In the modified form the narrow strip of photographic paper, and its driving mechanism, were replaced by a rectangular sheet wrapped

round a drum which is rotated by clockwork ; as the drum rotates it advances slightly along its axis, and, when there are no tremors, the record consists of a series of straight lines across the sheet. By this alteration Milne was enabled to run the record at four times the previous rate, and at the same time to halve the amount of photographic paper used. With the more open time-scale it was possible to study very small movements which could not be identified in the older records.

Seismographs with Mechanical Registration

The pendulum of a seismograph which records mechanically is connected by levers or by a long arm to a scribing point which rests on a smoked sheet of paper. The paper for this purpose is prepared by passing it through the sooty flame of an oil lamp. When the scriber moves across the paper the deposit of soot is removed leaving a fine white line against a black background. The paper is wrapped round a drum driven by clockwork. The drum is carried on a lead-screw and the rotation is accompanied by a slow traversing movement along the axis. The drum usually rotates about once an hour, and the daily record consists of a number of lines running horizontally across the sheet ; the separation between the successive lines is about five millimeters. The seismograph is constructed so that the displacements of the scriber due to pendulum movements are in a direction perpendicular to that of the undisturbed trace. The completed records are varnished to make them permanent.

The instruments of this type have one great advantage over the other types, for the records are visible while the seismograph is in operation. On the other hand there is an uncertain amount of friction at the pivots of the magnifying levers, and between the scriber and sheet. It is impossible to make a satisfactory allowance for friction in calculations of the amplitude, etc., of the earth-waves, and there-

fore for some purposes the records from these seismographs are unsatisfactory.

The most popular instrument of this type is the Wiechert. In this seismograph, Fig. 22,[1] an inverted pendulum is attached to a massive framework by crossed Cardan springs which form a universal joint. The mass of the pendulum varies from 80 kg. to 200 kg. but in some earlier models it was much larger. The mass is connected to two thrust arms set in directions at right angles; the connexions are arranged to act as stabilizers and make the inverted pendulum stable for small oscillations. Each thrust arm is connected to a lever which carries a stylus for recording.

The damping is due to the resistance of air to the motion of a piston in a cylinder. A piston is connected to each thrust arm and moves in a closely fitting cylinder; the air spaces at the ends of the cylinder are connected through a valve by which the resistance to the motion of the piston can be regulated. The damping can be cut off completely by opening holes through which air can enter or leave the spaces at the ends of the piston.

One large sheet of smoked paper is used for registration. The stylus arms are separated by a little less than half the width of the sheet and placed so that one component is recorded on the upper half and the other on the lower half. The recording sheet is pasted together at the ends to form a cylinder which is laid over the large drum shown at the left of the photograph; the paper hangs in a loop with an aluminium cylinder inserted at the bottom to keep it taut. The drum is rotated by a weight-driven clock, and carries the paper round at a speed of about 15 mm. per minute.

To determine the sensitivity a test-weight is added to one side of the main mass; the deflexion is noted and the static magnification can be calculated. The magnification can be varied from 40 to 160, and the period from 4 seconds to 12 seconds, by different settings of the levers. The instru-

[1] This is the type now manufactured by Messrs. Spindler and Hoyer of Göttingen, from whom the illustration has been obtained.

ments generally operate with a free period of about 6 seconds and a damping ratio of about 5 to 1.

A passing mention may be made of the Mainka and the Omori as other examples of horizontal pendulums with mechanical registration.

Seismographs with Direct Optical Registration

In these instruments a beam of light is reflected from a mirror connected to the pendulum, and focussed on to a moving sheet of photographic paper. The light beam serves as a long weightless pointer and some of the more serious difficulties associated with mechanical registration are eliminated. There is no friction at the paper surface or at pivots in the magnifying levers, and the moment of inertia of the moving system is less than when levers are connected to the pendulum. The three designs to be described show how various requirements are fulfilled with optically recording seismographs. The first is the Milne-Shaw, an easily maintained instrument for general recording, the second is the McComb-Romberg, in which a special coupling is used between the pendulum and mirror to compensate for tilting effects, and the third is the elegant high-magnification seismograph known as the Wood-Anderson.

The Milne-Shaw seismograph, shown in Fig. 23, is a modified and improved form of the Milne instrument. The magnification is partly mechanical and partly optical. The mass of ½ kg. is attached to a short aluminium arm and suspended in the manner shown in Fig. 16 (*a*). The end of the pendulum arm is connected by a very light strip of aluminium to a short lever which is balanced on a jewel bearing and carries the mirror at its other end; the mirror is concave with a focal length of 50 cms. A copper plate attached to the pendulum is carried between the poles of four horse-shoe magnets. The plate moves across the magnetic field as the pendulum oscillates, and the induced electric currents tend to oppose the motion of the pendulum.

The amount of damping can be adjusted by altering the position of the magnets relative to the plate; the damping-ratio usually adopted with the Milne-Shaw seismograph is 20 to 1. The advantage of magnetic damping is that the retarding force is strictly proportional to the velocity of the pendulum. For registration an image of a fine illuminated slit is reflected from the mirror and focussed on to the photographic sheet as a sharp spot of light. The time scale of the record is 8 mm. per minute. The coupler between the pendulum and mirror may be placed in either of two positions. The dimensions of the instrument are such that the static magnification is 250 with the coupler in one position and 150 for the other. In calibration, the instrument can be given a known tilt by means of a fine-adjustment screw attached to one of the feet. The free period is generally adjusted to be exactly 12 seconds or 10 seconds; with these periods the magnification falls to half of the static value for waves of periods about 15 seconds.

Seismographs which are not affected by slow tilting of the ground have been made in America by H. E. McComb and A. Romberg. The pendulums used for the experimental instruments were modified from old type Milne and Bosch-Omori seismographs. The connexion between the pendulum and mirror is made by what is termed a viscous coupling. This coupling is provided by the motion of a light brass vane immersed in oil. The vessel of oil is carried by the pendulum; the vane, which is slightly smaller than the cross-section of the vessel, is attached to a short lever from the mirror. Owing to the viscosity of the oil, the vane is moved by the pendulum as if the coupling were rigid for earth-movements with periods up to about 40 seconds, but for very slow movements the oil filters past the edges of the vane, and the mirror is not moved.

G. W. Walker, in his book *Modern Seismology* published in 1913, pointed out that the sensitivity of a seismograph does not depend upon the size of the mass; he suggested that it might be possible to make an instrument with a very

small pendulum and a fine Zöllner suspension of quartz fibres, which could be contained in a vessel the size of an ordinary tumbler. The instrument constructed by H. O. Wood and J. A. Anderson in 1925 is a remarkably accurate fulfilment of Walker's forecast.

The mass of the Wood-Anderson seismograph consists of a small copper cylinder weighing only 0·7 gm.; it is carried eccentrically on a stretched vertical wire. The control is due to the torsional reaction of the wire, and the free period is usually less than a second. The mass hangs between the poles of a strong magnet and the pendulum motion is damped nearly to the limit of aperiodicity. Recording is from a small mirror attached to the top of the mass. The magnification depends upon the ratio of the distance between the mirror and recording drum to the radius of the copper cylinder, and the latter is so small that a magnification of about 1,500 is easily obtained.

The Wood-Anderson is the best seismograph for the recording of earthquakes at distances up to about 1,500 km. Two of these instruments were constructed at Kew Observatory a few years ago, and have been modified to improve the efficiency for recording more distant earthquakes. By using larger masses, each weighing 3 gm., the magnification is reduced to 700 which is adequate for teleseismic recording. The instruments are set up with the axes slightly inclined to the vertical, and the control is chiefly due to gravity; they are adjusted to have free periods of 2½ seconds. Photographs of these instruments are reproduced in Fig. 24 and Fig. 25. The photograph, Fig. 24, shows one of the pendulums with the cover removed; the other illustration includes the two pendulums, set up to register the N.–S. and E.–W. components, the lighting system, and a large drum for recording both the components. The recording drum is one of the latest type driven by an alternating current electric motor instead of by clockwork. The advantage of an electrically driven drum is that the rate of rotation is much more uniform than that obtained with

a clockwork drive. The time-scale of the records obtained from drums of the type shown in the illustration is usually 15 mm. per minute, but in some cases may be larger.

Seismographs with Galvanometric Registration

To increase the magnification of his seismographs Galitzin introduced a new method depending on the principle that when a coil of wire moves across a magnetic field electric currents are set up in the wire. Several coils, joined in series and connected to a sensitive galvanometer, are carried by the pendulum and move between the poles of strong magnets. As the pendulum moves the current flowing through the galvanometer is proportional to the angular velocity of the pendulum. The deflexions of the galvanometer mirror are recorded photographically. The advantages of this method are that it gives a very high magnification, the instruments are not affected by tilting, and it is possible to have the pendulums and recording mechanism in different rooms. A set of three Galitzin pendulums is shown in Fig. 26. The vertical pendulum is placed between the two horizontal pendulums which are of identical design but set up at right angles to each other.

In the Galitzin pendulums the masses, each of 7 kg., are suspended in the manner shown in Figs. 16 (*c*) and 17 (*c*). Beyond the mass the moving system passes between the poles of two pairs of powerful horse-shoe magnets which are attached to the framework of the instrument. The coils of wire connected to the galvanometer are carried between the poles of the magnets nearer to the mass, and a large copper plate is carried between the poles of the outer magnets to provide the damping.

The theory of galvanometric registration has been worked out by Galitzin. The treatment of the problem is carried out in two stages; the first is the ordinary case of calculating the pendulum motion which corresponds with the earth-waves, the second is to determine how this motion of the

pendulum affects the galvanometer. The calculations are simplified considerably if the pendulum and galvanometer have the same free periods and both are critically damped. The instruments are usually adjusted to conform with these conditions. These instruments do not respond to waves of very short period since the deflexions of the galvanometer depend upon the velocity of the pendulum and not upon the displacement. As the period of the earth-waves

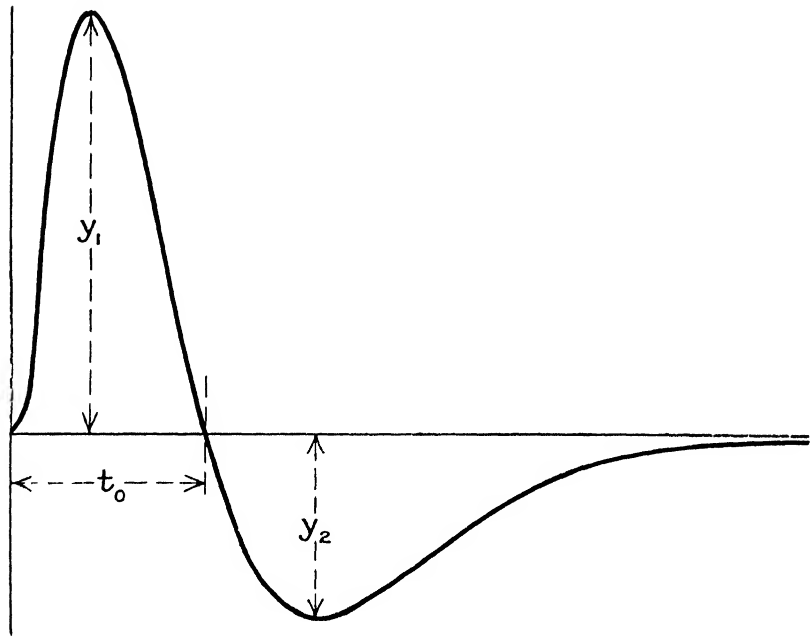


FIG. 27.—Motion recorded by Galitzin seismograph when pendulum is displaced

increases the magnification rises to a maximum value and subsequently falls off to zero for very slow waves; the greatest magnification occurs when the period of the earth-waves and the instrumental periods are in the ratio $1 : \sqrt{3}$. The damping of the galvanometer depends on the electrical properties of the circuit, and critical damping can be attained by inserting an additional resistance in series with the pendulum coils. To ascertain whether the pendulum has

the right period and is critically damped, the pendulum is given a small kick and the movements of the light spot reflected from the galvanometer mirror are examined. The spot moves to a maximum deflexion on one side, passes back through the zero to a maximum on the other side, and returns gradually towards the zero. The amplitudes on either side of the zero should be in a definite ratio, $y_1/y_2 = 2{\cdot}3$ (Fig. 27), and t_0, the time taken to return to zero at the end of the first swing, should be related to T, the instrumental period, according to the formula $t_0 = 3T/2\pi$.

In the Benioff seismographs an armature attached to the mass is separated by an air-gap from the poles of a magnet around which the coils are wound. Movement of the pendulum changes the magnetic flux and the current induced in the coils is recorded. The instruments have been adapted for the vertical as well as for the horizontal components. The magnification is high enough for a galvanometer of very short period to be used, and these seismographs are particularly suitable for the recording of local earthquakes.

Installation of Seismographs

It has been found that seismographs operating in a large exposed building are disturbed by the effects of wind on the building. The disturbance persists even if the instruments are placed on stone pillars which pass through holes in the floor and are sunk into the earth ; clearly the earth in the vicinity is set into motion as the building rocks in the wind. Similar disturbances have been found in the records of seismographs in buildings near tall trees. These disturbances can be avoided by placing the instruments in a lowish building about a hundred yards away from taller buildings or trees.

Pillars to carry the instruments can be built up from the floor if this is of solid stone or concrete. A wooden floor is not sufficiently rigid and the pillars should be carried down

through holes to a solid foundation beneath it. The instruments should be protected from draughts by airtight covers, and the room should not be subject to rapid changes of temperature. These changes are more serious for vertical than for horizontal seismographs. The elasticity of the spring which carries the mass depends upon the temperature, and if the temperature changes the pendulum drifts beyond the limits of registration. The difficulties of operation are diminished considerably if the spring is made of elinvar instead of steel, since this alloy has a temperature coefficient of elasticity about one-tenth that of steel, but even then the instrument must be well protected from temperature changes.

Provision must be made for accurate measurement of the times at which disturbances are shown in the records. For this purpose it is essential to have a first-class clock fitted with contacts for completing electrical circuits at the minute and at the hour. The clock must be checked regularly by comparisons with the broadcast time-signals, so that the error and daily rate can be determined accurately. At some observatories special instruments are used whereby the wireless signals are recorded on the seismograms.

In the Wiechert and some other seismographs with mechanical registration the current from the clock operates small electromagnets; the movements of the armatures displace the recording arms slightly to one side and each minute is shown by a tiny kick in the traces. Similar electromagnets, with small "flags" attached to the armatures, are frequently used with optical registration. When the clock circuit is completed the flag is moved and cuts off the light; the time marks are shown as breaks in the records. If several seismographs are in use it is convenient to pass the electrical circuit for lighting the instruments through a relay switch operated by the clock; the lights are then extinguished automatically when the circuit is completed. This is the system used at Kew Observatory where five instruments are in regular operation; the

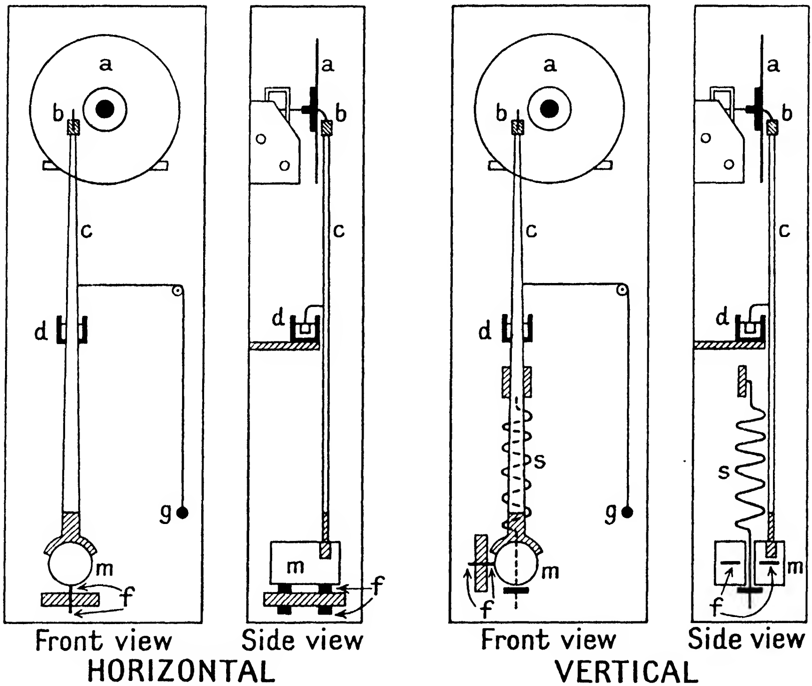
standard clock is a Synchronome which makes contact for two seconds at the beginning of each minute and for four seconds at the hour.

Seismographs for use in the Epicentral Region

Most of the seismographs described in the preceding sections are primarily instruments for recording teleseismic waves, but some, such as the Wood-Anderson and the Benioff, are suitable for recording the waves within a few degrees of the epicentre of small or moderate earthquakes. The motion around the epicentre of a severe earthquake, however, is too large, and too rapid, to be recorded with ordinary seismographs, and special instruments have been devised for use in regions where these earthquakes are frequently experienced. The instruments are of two types for measuring the accelerations and the displacements of the ground; those of the first type have a very short free period, whilst those of the second have a long period and very low magnification. It is natural that instruments of these types should have been used for a number of years in Japan; the earthquakes there are frequently so violent that for successful recording the earth movements must be reduced instead of magnified. More recently various instruments of improved designs have been installed at nearly 50 stations throughout California for recording the stronger earthquake movements; a complete description of these instruments is given in N. H. Heck's recent book *Earthquakes*. The records obtained from these instruments show that the motion around the epicentre of an earthquake is very complicated, with waves of different periods superposed. Among the most interesting of the results which have been published are those for the Long Beach earthquake of 10th March, 1933. In the more rapid movements near the epicentre of that earthquake the period was $\frac{1}{3}$ second, the maximum acceleration nearly a quarter that of gravity, and the greatest displacement 1 cm.; the slower movements

were of period $1\frac{1}{2}$ seconds, with the maximum acceleration one-tenth of gravity, and the displacement 12 cms. The records indicate that the more rapid oscillations were damped out within about 50 km. of the epicentre.

T. A. Jaggar, director of the volcanic observatory in Hawaii, has designed a simple type of instrument, termed



a, Smoked disc b, Stylus c, Magnifying lath d, Damper
f, Flat springs g, Gram weight attached for sensitivity test
m, Steady mass s, Spiral spring supporting mass of vertical instrument

FIG. 28.—Shock records for horizontal and vertical components

the Jaggar shock recorder, for recording the horizontal movements in regions where small earthquakes occur frequently. An inverted pendulum is carried by two flat springs in the manner shown on the left side of Fig. 28. The registration is mechanical by a stylus carried at the upper end of a light wooden lath which is attached to the

mass. The record is taken on a smoked circular disc of Bristol board, which is carried on the minute spindle of a small clock movement and rotates once an hour. The clock is carried on rollers which run on horizontal rails, and as the springs unwind the clock and recording disc are carried sideways. Hence, in the undisturbed record, the trace on the smoked sheet is a spiral. Attached to the recording lath is a light aluminium vane which is immersed in a damping pot containing oil. The deflexion of the stylus produced by attaching the weight shown on the right of the instrument gives a measure of the sensitivity ; this weight is not connected to the lath when the shock recorder is in operation. Several of these shock recorders, and also an instrument of similar type for the vertical component, were constructed at Kew Observatory for use by the expedition, sent out in 1936 by the Royal Society, to investigate the earthquakes in Montserrat, British West Indies. In the vertical instrument the mass is carried by a spiral spring, and its distance from the clamps is regulated by light flat springs.

CHAPTER VI

ELASTIC WAVES IN SOLIDS

THE fact that earthquakes, in addition to being felt over large areas, can be detected by instruments at great distances indicates that the disturbances are elastic waves which travel in the earth. It is therefore natural to consider the seismic observations in the light of the results obtained from theoretical studies of the wave motion in a solid body; in these investigations it is nearly always presupposed that the waves are propagated in a medium of uniform composition. An assumption of this sort does not agree with our ideas of the composition of the earth for we know that the rocks near the surface are of various kinds, differing in their physical properties. It must be emphasized, however, that only a very small fraction of the material constituting the earth is accessible for direct examination; in the first place the oceans cover nearly three-quarters of the surface, and secondly the deepest observations, such as those in mines and borings, only extend below the surface to two or three kilometres which depth is a very small fraction of the earth's radius (6,378 km. at the equator). Thus, although it is obvious that we cannot expect to get a complete representation of the seismic disturbances from the theories, we may hope to obtain information about the most important characteristics of the wave motion. This, in fact, has proved to be the case, but it will be shown later that the idea of a uniform solid earth must be abandoned and that there are some very remarkable changes in the structure of the globe at great depths.

The elastic properties of solids and fluids, and the characteristics of the elastic oscillations which travel outwards from a sudden disturbance in a solid body, are described in the following sections. The elastic waves are divided into two types, body waves which travel through the medium, and surface waves in which the oscillations are confined to a layer near the surface.

Elasticity

The subject of elasticity refers to the changes in the size or shape of a body acted upon by outside forces. In popular language the term elastic is confined to substances like india-rubber, and the properties of a block of india-rubber are convenient examples of those shown to a greater or lesser extent by all elastic bodies including the rocks through which the earthquake waves are propagated. If the pressure on all the surfaces of such a block is increased the material is compressed into a smaller volume, and when the pressure is decreased the material expands ; the forces produce changes of size but not of shape. The shape can be changed by applying opposing forces to opposite sides so that the block is distorted or strained ; the block resumes its original shape when the forces are removed, provided the distortion has not been carried too far. These two kinds of elastic deformations are shown in Fig. 29.

It is usual to refer to the forces which act on the body as " stresses ", and to the changes in shape or size as " strains " ; if the shape of the body is changed without alteration in the size, the strain is said to be a " shear ". The fundamental basis of the theory of elasticity is that the strains are proportional to the stresses which produce them. This relationship was enunciated about 300 years ago by Robert Hooke, a famous Oxford scientist, in the form " ut tensio sic vis ". The proportionality between stresses and strains holds so long as the stresses are not large enough to produce a permanent deformation of the material, i.e. provided the

deformation is not carried beyond the elastic limit. The accuracy of Hooke's Law has been confirmed from the results of numerous experiments. The ratio of the stress to the strain is known as a "modulus" of elasticity. The "bulk modulus", k, is that for change of volume without alteration of the shape, and the "modulus of rigidity", n, is that for a body subjected to a shear. The latter of these moduli is generally referred to as the "rigidity". If a uniform pressure, p, is applied in all directions to an

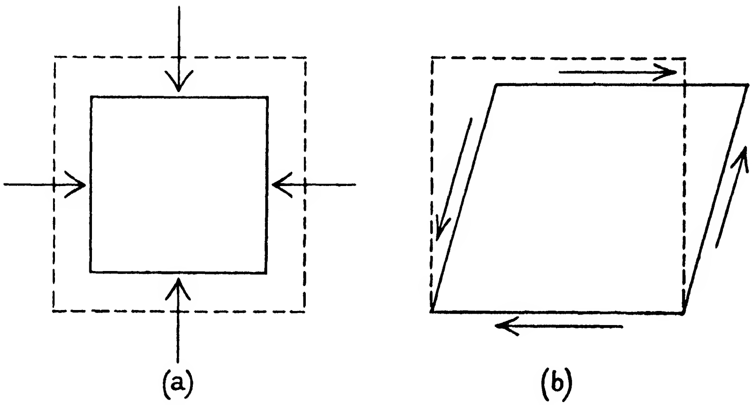


FIG. 29.—Elastic deformation. (*a*) Compression; (*b*) Distortion

elastic body and the volume is thereby changed from V to $V—v$, the percentage strain is v/V and k, the bulk modulus, is $\frac{p}{v/V}$. If the body is sheared through a small angle, θ, by the application of a stress, F, the rigidity, n, is F/θ.

The ordinary distinction between a solid and a fluid is that a solid retains a definite shape, but a fluid accommodates itself to the shape of the vessel which contains it; this is equivalent to saying that a solid possesses rigidity, and that the rigidity of a fluid is zero. A viscous substance like pitch may be very slow in assuming the shape of the vessel in which it is placed, but the fact that it eventually goes to the shape indicates that it has no rigidity and can be regarded as a fluid.

The rigidity of a body can be determined by experiment. For example, if we take a specimen of the material in the form of a cylinder of length l and radius r, and measure C, the couple required to twist one end through an angle θ relative to the other end, the rigidity is obtained from the equation $n = \frac{2Cl}{\theta \pi r^4}$, θ being measured in radians.

The bulk modulus cannot be determined so easily, for, when a specimen of the material is compressed or extended in the laboratory, the shape is usually changed as well as the volume. These changes occur when a wire is stretched by a weight hanging from it; the pull on the wire, which increases the length, stretches out the material and the sectional area becomes smaller. The quantities which can be measured directly are the Young's modulus, E, representing the ratio of longitudinal stress to strain, and Poisson's ratio, σ, denoting the ratio of the lateral strain to the longitudinal strain. Returning to the example of a wire stretched by a hanging weight, the Young's modulus is the ratio of the tension per unit area of cross-section to the elongation per unit length, and Poisson's ratio is the contraction per unit area of cross-section divided by the elongation per unit length.

The quantities E, σ, k and n are not independent; it has been shown that the relations between them are expressed by the formulæ:

$$E = \frac{9kn}{3k + n} \text{ and } \sigma = \frac{3k - 2n}{6k + 2n}.$$

The bulk modulus and the rigidity can therefore be calculated from the measured values of E and σ; the equations are $k = \frac{E}{3(1 - 2\sigma)}$ and $n = \frac{E}{2(1 + \sigma)}$. It will be seen subsequently that, for the materials in the earth, Poisson's ratio is approximately a quarter; for this value of σ, $k = \frac{2}{3}E$, $n = \frac{2}{5}E$ and the rigidity is three-fifths of the bulk modulus.

Among the best known measurements of the elasticity of rocks are the determinations carried out in 1906, under the auspices of the Carnegie Institution of Washington, at the McGill University, Montreal, by F. D. Adams and E. G. Coker. In these experiments the quantities determined were the Young's modulus and Poisson's ratio. Measurements were made for fifty-five specimens of rock, the specimens being cut in the shape of prisms, one inch square and three inches long, and of cylinders, one inch in diameter and three inches long. Pressures up to as much as 15,000 pounds per square inch were applied to the specimens, and the longitudinal compression and lateral extension were observed. Special instruments were designed or adapted for the tests and precautions were taken to ensure accuracy and consistency throughout the measurements. The rocks tested by Adams and Coker are representative of three groups ; the first group consists of marbles and limestone, the second of granites and the third of basic intrusive rocks ; the mean results for each of these groups are :

Type of rocks	*Average bulk modulus* (dynes per sq. cm.)	*Average Poisson's ratio*
Marbles and limestone . .	$4{\cdot}37 \times 10^{11}$	0·26
Granites	$3{\cdot}03 \times 10^{11}$	0·22
Basic intrusives . . .	$5{\cdot}72 \times 10^{11}$	0·26

These values refer to specimens collected from near the surface of the earth and maintained at a normal temperature. They cannot be taken as applicable to the rocks under the conditions which occur at great depths.

Body Waves

It has been known for many years that waves of two kinds, longitudinal and transverse, can be transmitted through a uniform solid body. The waves travel outwards in all directions from a disturbance, and during their passage the particles of the body are set in vibration. The motion of the particles is different for the two kinds of waves. In

the longitudinal waves, sometimes termed compressional waves, the particles move backwards and forwards in the direction in which the waves are travelling, and the material undergoes successive rarefactions and compressions like those in air through which a sound wave is passing. For the transverse or distortional waves the motion of the particles is perpendicular to the direction of travel, and the waves are similar to those which travel along a rope lying on the ground when it is moved sharply at one end. The longitudinal and transverse waves are represented diagrammatically in Fig. 30. The velocities of the waves depend upon ρ, the density of the medium, and the elastic co-

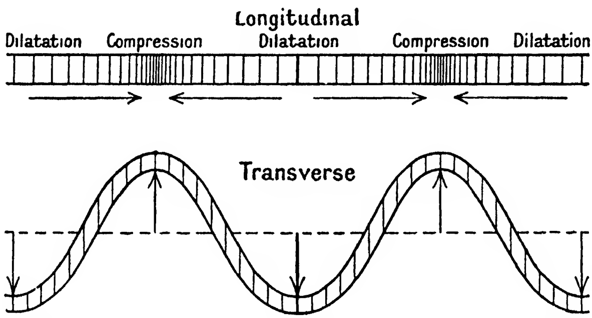


FIG. 30.—Motion of particles in longitudinal and transverse waves

efficients k and n. It can be shown that the velocities are $\sqrt{\frac{k + \frac{4}{3}n}{\rho}}$ and $\sqrt{\frac{n}{\rho}}$ for longitudinal and transverse waves respectively. For solids the velocity is greater for longitudinal than for transverse waves, and, for the particular case in which Poisson's ratio is a quarter, the speeds are in the ratio $\sqrt{3} : 1$. In fluids there can be no transverse waves and the velocity of the longitudinal waves is $\sqrt{\frac{k}{\rho}}$.

An idea of the speeds to be expected for waves in the earth can now be obtained. Of the specimens examined by Adams and Coker the basic intrusive rocks are on the average the least compressible; the density of these rocks

is about 2·8 grams per cubic centimetre. Hence, with $k = 5{\cdot}72 \times 10^{11}$ dynes/cm.^{2}, $\sigma = \frac{1}{4}$, $\rho = 2{\cdot}8$ gm./cm.^{3}, the velocity of the longitudinal waves is just over 6 km./sec, and that of the transverse waves is $3\frac{1}{2}$ km./sec. For water at normal temperatures k is about 2×10^{10} dynes/cm.^{2}, and the velocity of longitudinal waves, 1·4 km./sec., is over four times that of sound waves in air.

Waves incident upon a boundary separating two media,

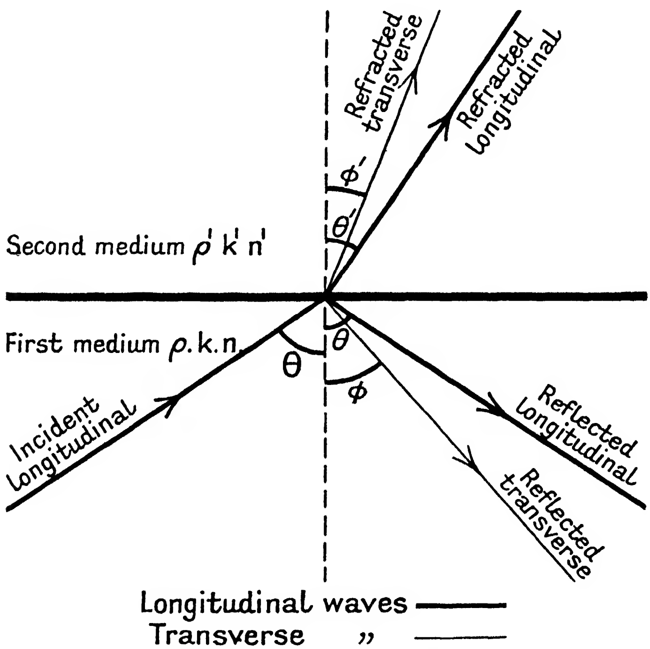


FIG. 31.—Reflexion and refraction from incident longitudinal waves

in which the velocities are different, undergo changes of type as well as reflexion and refraction. The incident waves, either longitudinal or transverse, may be split up into four parts—reflected, longitudinal and transverse, and refracted, longitudinal and transverse. Under special conditions some of the waves may be missing. The four waves derived from incident longitudinal waves are shown in Fig. 31. The ordinary laws of reflexion and of refraction may be used

for calculation of the angles between the different waves and the normal to the boundary. Let θ and ϕ represent these angles for longitudinal and transverse waves in one medium (ρ, k, n) and let θ' and ϕ' be the corresponding angles in the second medium (ρ', k', n'). Then the angles and velocities of the waves are connected by the formulæ—

$$\sin\theta : \sin\phi : \sin\theta' : \sin\phi' = \sqrt{\frac{k+\frac{4}{3}n}{\rho}} : \sqrt{\frac{n}{\rho}} : \sqrt{\frac{k'+\frac{4}{3}n'}{\rho'}} : \sqrt{\frac{n'}{\rho'}}.$$

The laws governing the distribution of energy between the four derived waves have been worked out by C. G. Knott. An important example, worked out in Knott's paper, is that of a discontinuity between rock and air. It is shown that oscillations of the ground are readily followed by the air; only a very small fraction of the energy passes into the air, most of it being reflected back into the ground.

Surface Waves

Our knowledge concerning waves propagated along the plane surface of an elastic solid is founded on the classical paper [1] by the third Lord Rayleigh; the subject investigated is "the behaviour of waves upon the plane free surface of an infinite homogeneous isotropic elastic solid, their character being such that a disturbance is confined to a superficial region of thickness comparable with the wave length. The case is thus analogous to that of deep water waves, only that the potential energy here depends upon elastic resilience instead of upon gravity." These waves are known as Rayleigh waves. The movements of the particles during the passage of the waves are in a vertical plane in the direction of propagation; there is no transverse horizontal component.

Lord Rayleigh applied the theory which he had developed

[1] Proceedings of the London Mathematical Society. Volume 17, 1885.

to two particular cases; one of these refers to an incompressible solid and is not of practical importance since in such a body the velocity of the longitudinal waves is infinite; the other is for a solid in which Poisson's ratio is $\frac{1}{4}$. In the latter case it is found that the velocity of propagation of the surface waves is 0·919 times that of the transverse waves; for Rayleigh waves of period T and wave length λ, the horizontal and vertical displacements, u and w, may be expressed in the form

$$u = F_1 \sin 2\pi\left\{\frac{t}{T} + \frac{x}{\lambda}\right\}$$

$$w = F_2 \cos 2\pi\left\{\frac{t}{T} + \frac{x}{\lambda}\right\}$$

t being the time and x the horizontal distance from the origin. The factors F_1 and F_2 depend upon z, the depth below the surface, and upon λ; each of these factors is the sum of two exponential functions, the formulæ from which the values can be calculated being

$$F_1 = A\left\{e^{-5\cdot325\frac{z}{\lambda}} - 0\cdot577e^{-2\cdot471\frac{z}{\lambda}}\right\}$$

$$F_2 = -A\left\{0\cdot848e^{-5\cdot325\frac{z}{\lambda}} - 1\cdot468e^{-2\cdot471\frac{z}{\lambda}}\right\}$$

where A is a constant governing the amplitude. At the surface $z = 0$ and the displacements, u_0, w_0, are given by the equations

$$u_0 = 0\cdot423\, A \sin 2\pi\left\{\frac{t}{T} + \frac{x}{\lambda}\right\}$$

$$w_0 = -0\cdot620\, A \cos 2\pi\left\{\frac{t}{T} + \frac{x}{\lambda}\right\}$$

On combining the values of u_0 and w_0 we find that the earth particles at the surface move in ellipses with the greatest horizontal displacement 0·68 of the greatest vertical displacement; the motion of the particles is retrograde, being opposite to that of a point on a wheel rolling on the ground in the direction of propagation.

To investigate the movements inside the solid various values are assumed for the ratio $\frac{z}{\lambda}$ and the bracketed terms in the expressions for F_1 and F_2 are evaluated. It is convenient to express the displacements calculated from these formulæ as percentages of the horizontal value at the surface. The values for depths down to twice the wave length are shown graphically in Fig. 32. The variations in the displacements are rather complicated. As the depth

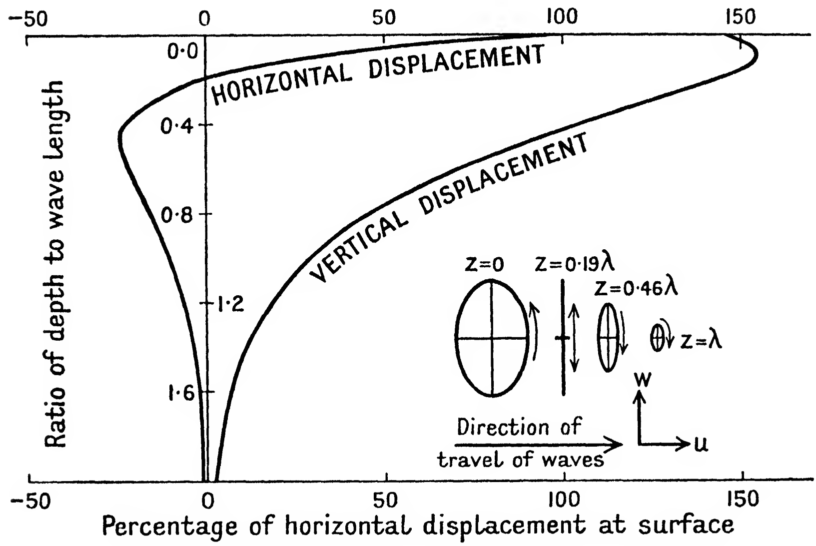


FIG. 32.—Relation between displacement and depth for Rayleigh waves

increases the horizontal movements diminish, and in passing through zero their direction relative to that of the vertical component is changed; at greater depths this reversed motion attains a maximum and subsequently diminishes. The vertical movements increase slightly at first and then get less and less. At a depth equal to the wave length the horizontal displacement is reduced to a tenth and the vertical displacement to a fifth of the value at the surface; if this depth is doubled there is a further tenfold reduction in the size of the movements. The insets to the diagram are

examples of the motion of the particles at different depths; the direction of travel of the waves is taken from left to right, so at the surface the motion is anticlockwise. The direction of motion is reversed at depths exceeding $0 \cdot 19\lambda$, where there is no horizontal motion the particles moving up and down through about the same range as at the surface; the cases illustrated for greater depths are those of $z = 0 \cdot 46\lambda$ corresponding with the greatest horizontal displacements in the reversed direction, and of $z = \lambda$. The limiting value of the ratio of the horizontal to vertical displacements at very great depths is $-0 \cdot 39$.

The theory of Rayleigh waves in a homogeneous medium covered by a superficial layer of other material has also been worked out. It is found that the velocity of the waves, and the amplitudes of the horizontal and vertical movements, depend upon the ratio of the wave length to the thickness of the layer and upon the differences between the properties of the media. Obviously if the wave length is very small the disturbance is not affected by the subjacent material, and for very long waves the properties of the layer are of little importance. The effect of a comparatively thin layer is less for the vertical than for the horizontal component. The ratio of the greatest horizontal and vertical displacements depends upon the wave length and thickness, and the horizontal motion may be as large as or greater than the vertical.

In early studies of the records of earthquakes it was noted that well-developed surface waves were sometimes shown several minutes earlier in the horizontal components than in the vertical, and that in the waves with no vertical component the motion was transverse. An explanation of these waves was published in Professor A. E. H. Love's essay, *Some Problems of Geodynamics*, which gained the Adams Prize of Cambridge University in 1911, and they have been named after him. Love showed that transverse surface waves, with no vertical motion, occur when an infinite solid is covered by a layer of finite thickness in which trans-

verse waves travel more slowly; the oscillations occur in a horizontal plane and are at right angles to the direction of propagation. These waves are usually referred to as Love waves, but sometimes the German designation *Querwellen* is used. The speed at which they travel depends upon the wave length, the thickness of the layer, and the properties of the media, the velocity of very short waves being that of transverse waves in the layer. It will be recalled that the velocity of the Rayleigh waves in any medium is 0·919 times that of the transverse waves; we see therefore that the velocity of Love waves is greater than that of Rayleigh waves. According to the theory of Rayleigh waves in a homogeneous solid the whole of the train of these waves would travel with the same velocity. For a medium in which the properties vary with the depth the velocities of Rayleigh and Love waves depend upon the wave length, and the disturbances are spread out into trains of waves.

CHAPTER VII

RECORDS OF EARTHQUAKES

EXAMINATION of the records obtained from the seismographs in use towards the end of the nineteenth century led to the division of the records into two parts which were termed the "preliminary tremors" and the "main shock". The records obtained from modern seismographs give the movements of the ground due to an earthquake in great detail, and show that the preliminary tremors are composed of sudden movements occurring at irregular intervals and perhaps followed by several oscillations. The movements in the main shock are more regular, the ground oscillating with a period which may vary from several seconds to several minutes; these oscillations are divided into successive groups of waves, in each of which the amplitudes increase progressively for several minutes and then subside. The movements, from large distant earthquakes, persist for hours and slowly diminish until they are too small to be recognized in the records.

It was at first believed that the preliminary tremors and the main shock might be due to longitudinal and to transverse waves respectively, and efforts were made to correlate the movements with the distance from the epicentre. No satisfactory results could be obtained and the nature of the phenomena was not discovered until 1900 when R. D. Oldham showed that the main shock represented the surface waves and that the longitudinal and transverse waves are both recorded in the preliminary tremors. Since the speed of the longitudinal waves in any medium is greater than that of the transverse waves, the time interval between the

arrivals of these two kinds of waves at any observatory depends upon the distance from the epicentre, increasing as we go further away. Oldham examined the times taken by the waves in travelling to different epicentral distances, and constructed a table showing the distances which correspond with specified time intervals between the arrivals of the longitudinal and transverse waves. With the subsequent improvements in the observations Oldham's table was soon superseded, but his discovery that the two kinds of waves could be identified in the seismograms marked the beginning of a new epoch in instrumental seismology.

TYPES OF SEISMIC WAVES

A notation to facilitate the description of the different kinds of waves, or " phases ", shown in the seismograms was introduced in 1904 by E. Wiechert and G. von dem Borne. The phases are classified as :

P (*undae primae*). The longitudinal waves which are the first to arrive.
S (*undae secundae*). The transverse waves which are the second main group.
L (*undae longae*). The surface waves which are oscillations of comparatively long periods.
M (*undae maximae*). The largest movements in the surface waves.

If the beginning of a phase is sharp it is denoted as " *i* " (*impetus*), if gradual or indistinct it is shown as " *e* " (*emersio*) ; these letters are added as prefixes to the phase symbols. This notation, in an amplified form, is still in use. The P and S waves have aptly been described as the " push and pull " and " shear and shake " waves.

Fig. 33 is a reproduction of an earthquake record in which the P, S, L and M movements are clearly shown. This seismogram was obtained on 8th March, 1931, from the Milne-Shaw instrument, at Stonyhurst College Observatory, Lancashire, which records the E.–W. component

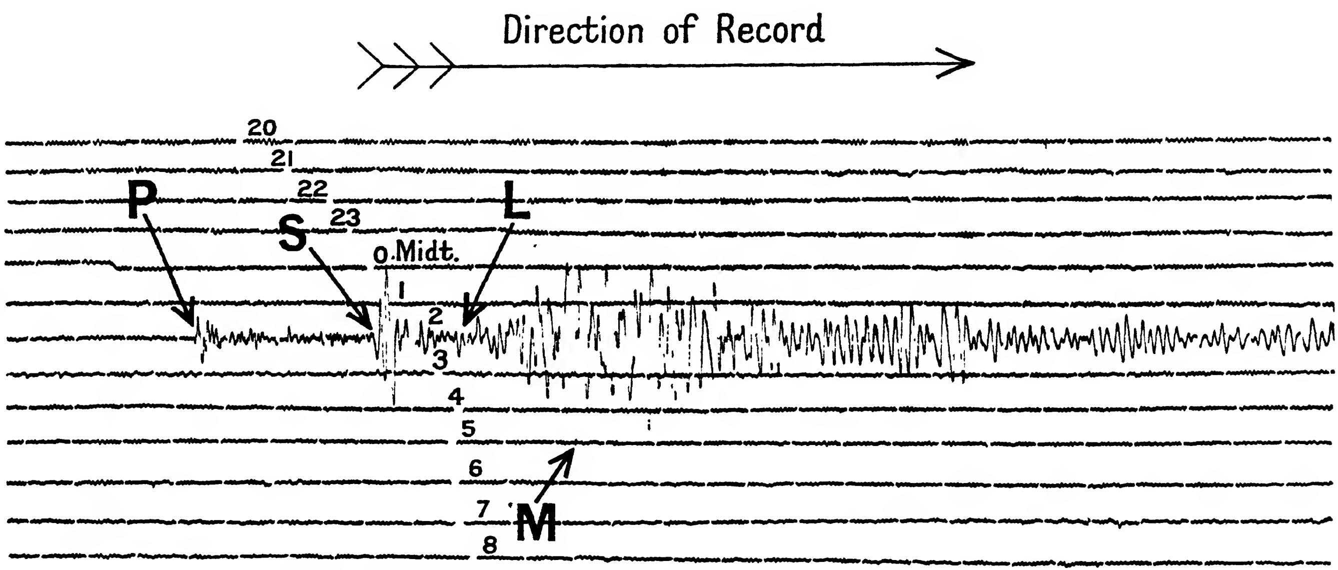


FIG. 33.—Stonyhurst record of earthquakes in Yugo-Slavia, 8th March, 1931

of the ground movement. The earthquake occurred in Yugo-Slavia, at a distance of 2,330 km. from Stonyhurst. The P waves start with a sharp movement of the light spot followed for several minutes by irregular small movements; the S waves begin with a larger kick, and the largest movements occur among the surface waves.

Following the identification of the longitudinal and transverse waves it was not long before other onsets, in the earlier parts of the records, were recognized as waves which had been reflected near the surface of the earth between the epicentre and recording station. The reflexions may be accompanied by changes of type of the waves from longitudinal to transverse, or *vice versa*. The phase symbols are repeated to indicate the reflected or transformed waves; thus, PP, PPP . . . are longitudinal waves reflected once, twice, etc., near the surface, SS, SSS . . . are reflected transverse waves, and PS, PPS, PSS . . . are waves which undergo changes of type on reflexion. The transformed waves are more complicated than is implied in this classification for there may be two or more waves (such as PPS, PSP, SPP) of different character but arriving almost simultaneously at the recording station. The paths of some of the reflected and transformed waves in travelling through the earth are shown in Figs. 35 and 36. The reflected waves are well shown in the records of the Galitzin seismographs at Kew Observatory for the earthquake near northern Japan on 11th September, 1935. In the N.–S. component (Fig. 34) the SS waves are very large. The onsets of the two types of surface waves are marked as L_Q for the Love waves (*Querwellen*), and L_R for the Rayleigh waves.

Beyond about 105° from the epicentre the P and S waves become very feeble and it is difficult to identify them in the records, but at 142° the P waves reappear in a modified form. The times of travel for these resuscitated waves are longer than those which would be expected for the ordinary P waves. These observations show that the velocity of the

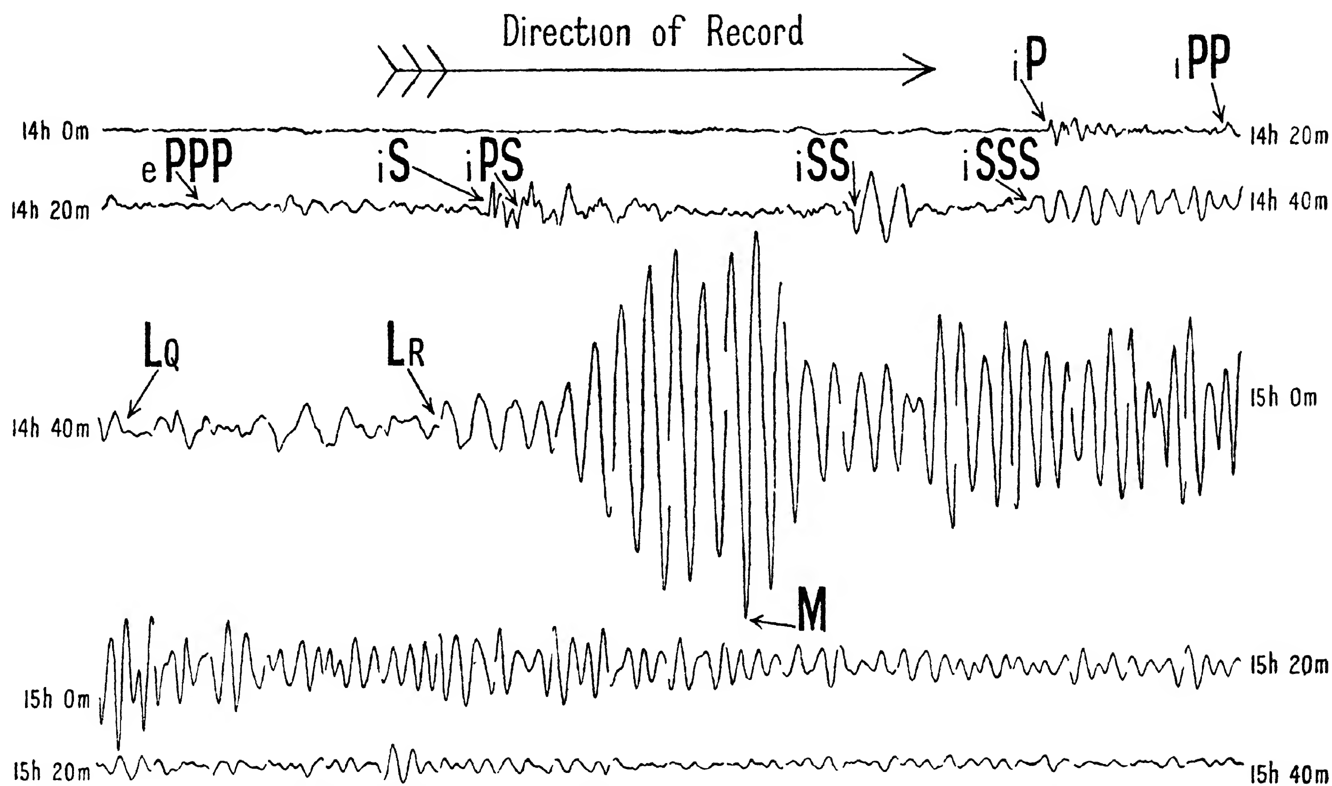


FIG. 34.—Kew record of earthquake near northern Japan, 11th September, 1935

longitudinal waves must decrease considerably somewhere beyond the greatest depths reached by the waves which emerge at a distance of 105°, and the fact that the transverse waves do not reappear suggests that the material at the greater depths has no rigidity. To explain these results R. D. Oldham put forward the hypothesis, in 1906, that the earth is composed of a plastic or liquid central core surrounded by a rocky shell. We now know that the discontinuity which occurs at the boundary of the core is located at a depth of about 2,900 km. from the surface. Transverse waves cannot exist in the core, but longitudinal and transverse waves reaching the boundary may on refraction pass through it as longitudinal waves.

The waves penetrating the core offer an explanation of further phases in the seismograms of distant earthquakes. Using the symbol K (from *Kernwellen*) which has recently been adopted to represent the longitudinal waves through the core, the most important of these phases are:

PKP, longitudinal waves throughout the whole of the path,
PKS, longitudinal waves passing into the core and transformed on emergence into transverse waves,
SKS, transverse waves which pass through the core as longitudinal waves,
SKSP, derived from SKS by reflexion and change of type near the surface,
PKKP and SKKS, which are waves reflected inside the core.

The waves which are reflected from the core but do not penetrate it are indicated as P_cP, P_cS and S_cS respectively. The waves P_cP and S_cS are clearly recorded in many seismograms, but they are less conspicuous than the P and S waves reflected near the surface; P_cS is rarely shown and is of theoretical rather than practical interest.

At the limiting distance for the transmission of P and S, these waves penetrate to the boundary of the core and become P_cP and S_cS. Slightly steeper P waves are refracted towards the normal at the point where they strike the core and reach the surface as PKP at a minimum

distance of 142° ; for the transformed waves (PKS) the corresponding minimum distance is 132°. Thus for longitudinal waves the core produces a shadow zone, or blind spot, in which neither the direct P nor the refracted PKP can occur ; in this region the reflected waves, PP, are the first strong movements shown in the seismograms. The longitudinal waves in the core travel faster than the transverse waves outside it and S waves are refracted as K away from the normal ; hence, instead of a shadow zone showing neither of the waves, there is a region of overlap in which both S and SKS are recorded. The S and SKS waves arrive simultaneously near 81°, where the greater speed of the deeper SKS is just sufficient to make up for the longer path ; at greater epicentral distances SKS arrives before S.

Owing to the differences between the velocities of the waves on either side of the boundary, the core acts like a lens which is convergent for the longitudinal waves and divergent for the transverse waves. Longitudinal waves penetrating the core are brought to a focus, and the amplitudes are large where they first reach the surface near 132° for PKS and 142° for PKP. On the other hand incident transverse waves are spread out and weakened in passing through the core as longitudinal waves.

Fig. 35 represents the paths of the waves from an earthquake of normal focal depth to a recording station at a distance of 60°. The body waves shown are the normal P and S, the first and second reflected waves, (PP, PPP, SS, SSS) and the waves reflected from the boundary of the core (P_cP, S_cS). The same paths are drawn for the longitudinal and transverse waves ; this is not actually the case but the differences are much too small to be appreciable in the diagram. The slight concavity of the paths towards the surface is due to the variation with depth in the velocity of the waves. The Love and Rayleigh waves, of course, travel near the surface of the earth.

The complexity of the movements at great distances from an earthquake will be appreciated from Fig. 36, which shows

the paths of the waves identified in the Kew seismograms for the great New Zealand earthquake of 2nd February, 1931. The earthquake was situated about 170° from the Observatory, and the records therefore showed waves reflected from the major, as well as the minor, arc of the great circle through Kew and the epicentre. The PKP

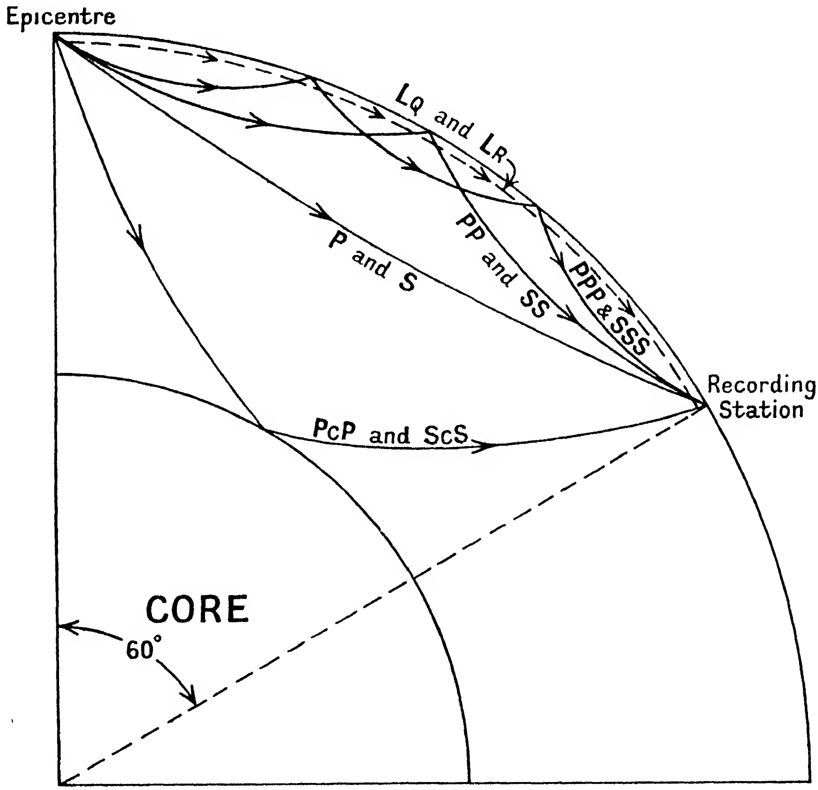


Fig. 35.—Paths of waves to an epicentral distance of 60°

phase was shown as two separate impulses (Fig. 37), corresponding with the paths of lesser and of greater deviation respectively; the duplication of this phase had been predicted theoretically by B. Gutenberg, and the two impulses were first observed by Miss I. Lehmann in the European records of the New Zealand earthquake of 16th

June, 1929. Other waves through the core which were well recorded at Kew from the 1931 earthquake are PKS, SKS, the transformed wave SKSP, and the internally reflected SKKS.

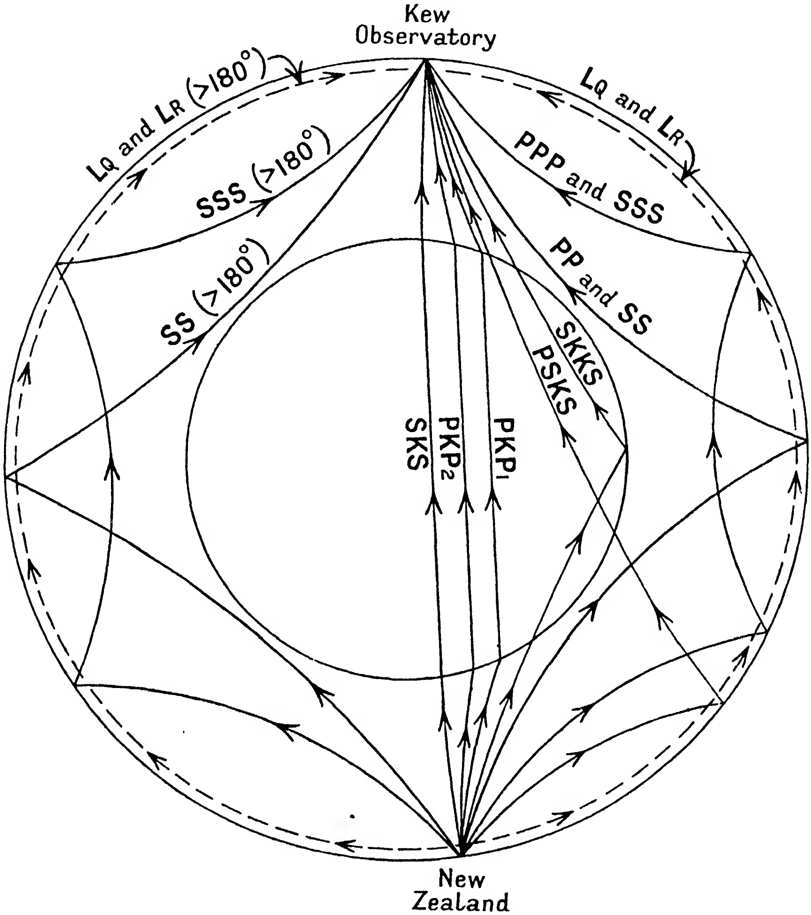


Fig. 36.—Paths of waves recorded at Kew Observatory from the New Zealand earthquake of 2nd February, 1931

Times of Travel of the Waves from Normal Earthquakes

The paper by Oldham, referred to on page 87, gives an early attempt to construct a table showing the times taken

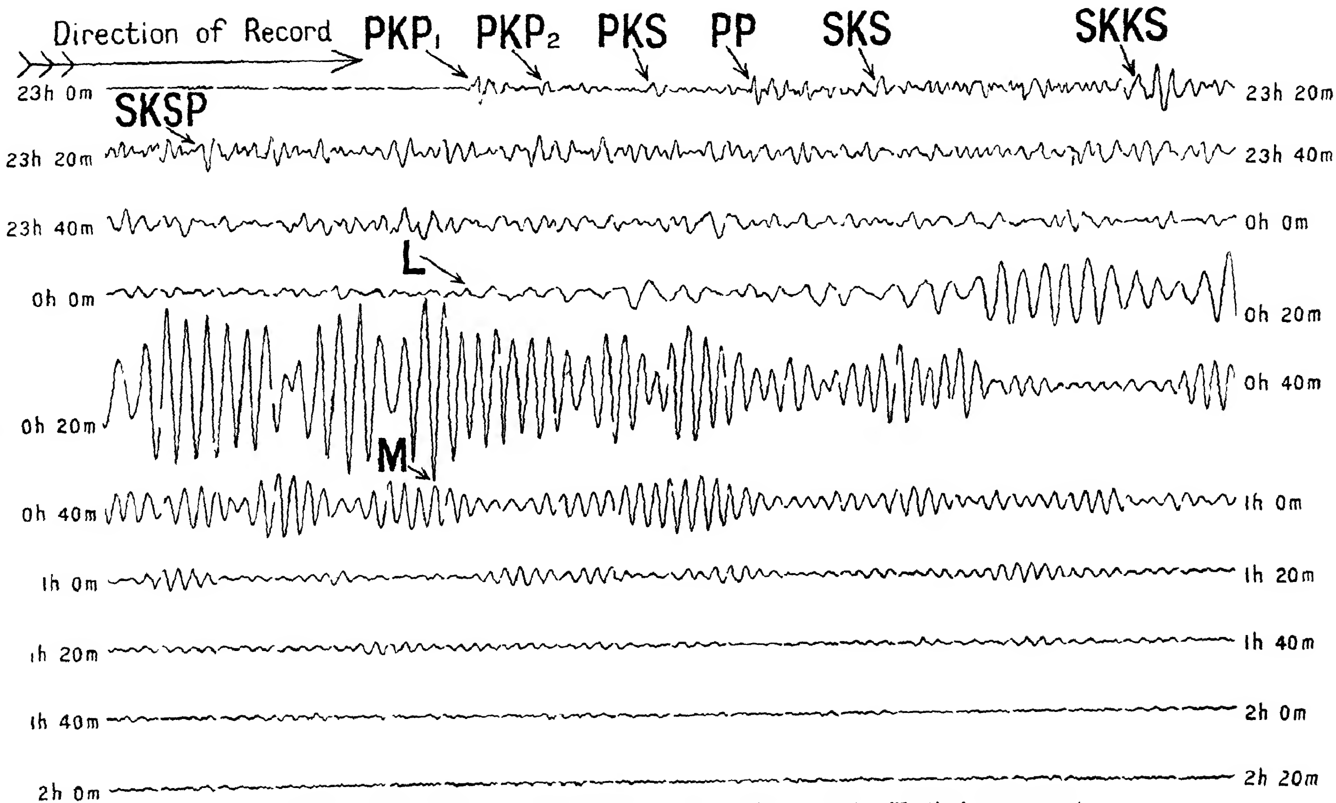


FIG. 37.—Kew record of New Zealand earthquake of 1931. Vertical component

by the P, S and L waves in travelling to different distances from the epicentre. The data available for the examination of the travel-times has increased enormously since Oldham's paper was written and numerous other sets of tables have been prepared. Most of the investigations have followed one or other of the following methods:

(i) the analysis of a large number of seismograms for one or more selected earthquakes,

(ii) statistical studies based upon data published from the various observatories or in the International Seismological Summary.

Each method has its merits and its disadvantages; the former has the advantage of uniformity in tabulation, for with the measurements all made by the same person the seismograms from adjacent stations can be compared; by using the second method the investigator has a great deal more material available for the work, and avoids the laborious measurement of the records.

Among the best known of the travel-time tables may be mentioned those due to H. H. Turner (1926),[1] J. B. Macelwane (1933), B. Gutenberg and C. F. Richter (1934), and to H. Jeffreys and K. E. Bullen (1935). There were many inconsistencies among the earlier tables, a frequent source of trouble being the inclusion of data for earthquakes of abnormal focal depth. It has been recognized in the last few years that some earthquakes occur at much greater depths than the majority of shocks, and that special tables are required for these earthquakes. The "normal" earthquakes all occur within some 50 km. of the earth's surface and their average depth of focus is about 30 km. With the more reliable observations now available, the latest tables of travel-times for normal earthquakes, as given by different

[1] These tables were derived from the observations collected by K. Zöppritz for the earthquakes which occurred during 1905 in Calabria on 8th September, in India on 4th April, and in California on 18th April, and are frequently referred to as the Zöppritz-Turner tables. They were used in the International Seismological Summary until 1929 but in the subsequent volumes have been superseded by the Jeffreys-Bullen tables.

investigators, are in good agreement. The P travel-times now in use are believed to be accurate to within a second; the uncertainties for S are greater owing to the difficulties of selecting the exact time at which this phase first appears in the records.

In most of the investigations of the propagation of seismic waves the distances between the epicentres of the earthquakes and the recording stations have been calculated on the assumption that the shape of the earth is spherical. Professor Turner, in 1915, published an account of the method he had found most convenient for estimating the distances; the method is equivalent to the use of Cartesian co-ordinates. Taking the origin at the centre of a sphere of unit radius, let a, b, c and A, B, C be the co-ordinates of two points on the surface. Then Δ, the angular distance between these points, can be computed from either of the formulæ—

$$2(1 - \cos \Delta) = (a - A)^2 + (b - B)^2 + (c - C)^2$$
$$\text{and } \cos \Delta = aA + bB + cC$$

If ϕ be the latitude, measured to the north, and λ the longitude, measured to the east, for a point on the globe, then

$$a = \cos \phi \cos \lambda,\ b = \cos \phi \sin \lambda,\ c = \sin \phi.$$

Actually the earth is spheroidal, the equatorial radius being 6,378 km. and the polar radius 6,357 km. Hence the co-ordinates, a, b, c, are the direction cosines of the vertical at the given point, and Δ is the angle between two verticals. In seismological investigations it has hitherto not been necessary to allow for the departure of the globe from a sphere, and Δ has been regarded as the distance between the two points. The errors which may be introduced on this account in the reduction of the observations are usually less than a second for P and less than two seconds for S, but the observations have now improved to such an extent that these uncertainties must be eliminated. A modified procedure has been worked out for computations of the

distances on the spheroidal earth and will shortly be brought into use.

The times of travel to different distances for various other waves have been determined, either by calculation from the travel-times of P and S, or from the observations. The onsets of some of the waves are not clearly shown in the majority of the records and the accuracy of the tables is not so good as that for the main waves. The methods used in calculation of the times for the derived waves were developed by B. Gutenberg in 1914; the results he obtained were set out in the form of a diagram showing the relation between the times of travel for different waves and the epicentral distance.

Gutenberg's diagram, reproduced in an amended form in Fig. 38, is of great value for rapid identification of the phases in an earthquake record, and for obtaining rough values of the epicentral distance and time of origin; it applies, of course, only to earthquakes of normal focal depth. In practice the onsets of the phases and the commencements of the surface waves are timed from the records and plotted on a strip of paper to the time-scale of the diagram; the strip is placed on the diagram in a vertical position, and moved about until the best fit between the observed times and the curves is found; the epicentral distance, time of origin, and identifications of the phases are then read off from the diagram.

In the table on page 101 are given the times of travel for P and S, and the interval between these onsets, at distances up to 104°. The values were obtained[1] from a study of the data published in the International Seismological Summary, 1930 and 1931, for 146 important earthquakes. The times in the table, and those of Fig. 38, are reckoned from the time of occurrence of the earthquake at the focus.

[1] London, Meteorological Office, *Geophysical Memoirs*, No. 76, 1938.

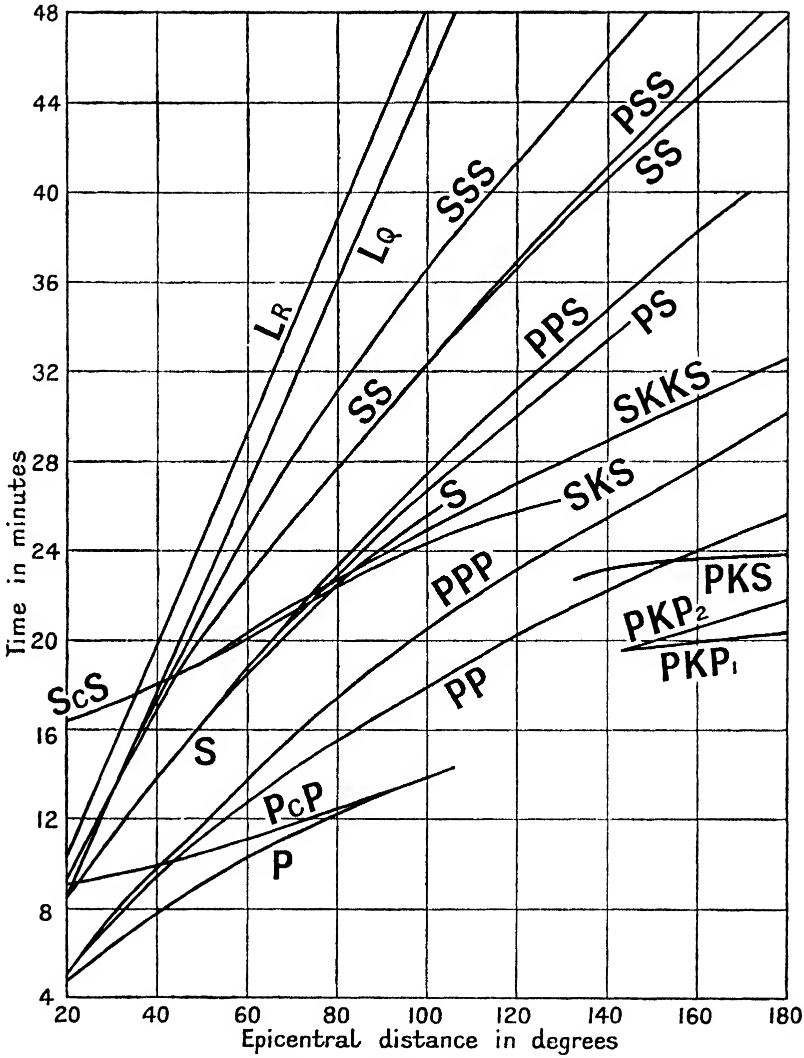


FIG. 38.—Times of travel of seismic waves to different distances

NEAR EARTHQUAKES

The study of the records obtained within say 1,500 km. from the epicentre of earthquakes has yielded valuable information about the constitution of the outer layers of

TIMES OF TRAVEL FOR P AND S WAVES

Distance	P	S	S − P
°	m. s.	m. s.	m. s.
0	(0 6)	(0 6)	(0 0)
1	20	32	12
2	35	59	24
3	49	1 25	36
4	1 3	51	48
5	17	2 17	1 0
6	31	42	11
7	45	3 8	23
8	59	34	35
9	2 13	59	46
10	27	4 25	58
11	41	51	2 10
12	54	5 16	22
13	3 8	42	34
14	21	6 8	47
15	35	32	57
16	47	55	3 8
17	4 0	7 17	17
18	13	38	25
19	25	58	33
20	36	8 18	42
21	46	38	52
22	57	57	4 0
23	5 7	9 16	9
24	16	34	18
25	26	52	26

Distance	P	S	S − P
°	m. s.	m. s.	m. s.
26	5 35	10 8	4 33
27	44	24	40
28	53	39	46
29	6 2	55	53
30	11	11 10	59
31	20	25	5 5
32	29	41	12
33	38	56	18
34	46	12 12	26
35	55	27	32
36	7 4	42	38
37	12	57	45
38	21	13 13	52
39	30	28	58
40	38	43	6 5
41	46	58	12
42	55	14 13	18
43	8 3	27	24
44	11	42	31
45	19	57	38
46	27	15 11	44
47	35	26	51
48	42	40	58
49	50	54	7 4
50	57	16 8	11
51	9 5	22	17

Distance	P	S	S − P
°	m. s.	m. s.	m. s.
52	9 12	16 36	7 24
53	20	49	29
54	27	17 3	36
55	35	16	41
56	42	30	48
57	49	43	54
58	56	56	8 0
59	10 3	18 9	6
60	11	22	11
61	18	34	16
62	24	47	23
63	31	19 0	29
64	38	12	34
65	45	25	40
66	51	37	46
67	58	49	51
68	11 4	20 1	57
69	11	13	9 2
70	17	25	8
71	23	37	14
72	29	48	19
73	35	21 0	25
74	41	11	30
75	46	22	36
76	52	33	41
77	58	44	46

Distance	P	S	S − P
°	m. s.	m. s.	m. s.
78	12 3	21 55	9 52
79	9	22 6	57
80	14	17	10 3
81	19	28	9
82	24	38	14
83	29	49	20
84	34	23 0	26
85	39	10	31
86	44	20	36
87	49	30	41
88	54	40	46
89	59	50	51
90	13 3	59	56
91	8	24 8	11 0
92	13	17	4
93	17	26	9
94	22	35	13
95	27	43	16
96	31	52	21
97	36	25 1	25
98	40	9	29
99	45	18	33
100	50	26	36
101	54	34	40
102	59	42	43
103	14 3	50	47
104	8	58	50

the earth's crust. A. Mohorovičić, a Serbian seismologist, who had examined the records of the earthquake in the Balkans on 8th October, 1909, was the first to point out that at some distances the records contain two clear onsets of the longitudinal and two of the transverse waves. He found that the ordinary P and S waves could be identified to within about 100 km. from the epicentre, but at the smaller of these distances each of the onsets was followed by another pulse. In the regions very close to the epicentre only the additional pulses were recorded. Mohorovičić concluded that the additional pulses were due to waves which travelled through a layer near the earth's

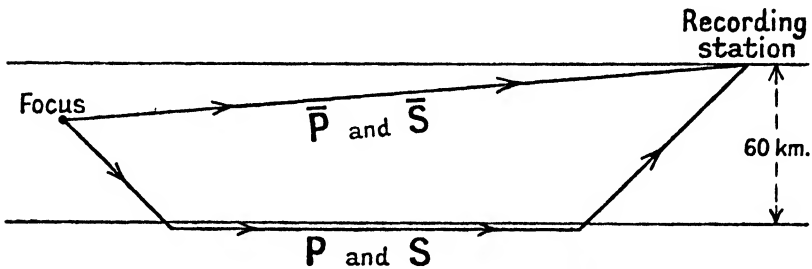


FIG. 39.—Paths of waves $\bar{P}$,P,S,$\bar{S}$

surface, and that the normal P and S waves travelled in the rocks beneath a discontinuity at a depth of 60 km. (Fig. 39); he adopted the notation $\bar{P}$, $\bar{S}$, for the waves in the upper layer, but these symbols have subsequently been replaced by P_g, S_g, which are more convenient for printing. A third onset of P was found in the records of the Tauern earthquake of 28th November, 1923, by V. Conrad, who suggested that it is a wave travelling in an intermediate layer and termed the pulse P* ; the corresponding transverse phase, S*, was later found by Jeffreys in the records of the Jersey earthquake of 30th July, 1926. Other pairs of pulses have sometimes been identified in the records of particular earthquakes, but the waves P, P_g, S, S_g, are the only ones clearly shown in most of the records. Fig. 40 is an illustration of records showing all six of the waves ;

these are the seismograms obtained at Hongo, Tokyo, at an epicentral distance of 419 km. from the Tango earthquake of 7th March, 1927.

The velocities of the waves have been determined from observations of numerous earthquakes, and are constant

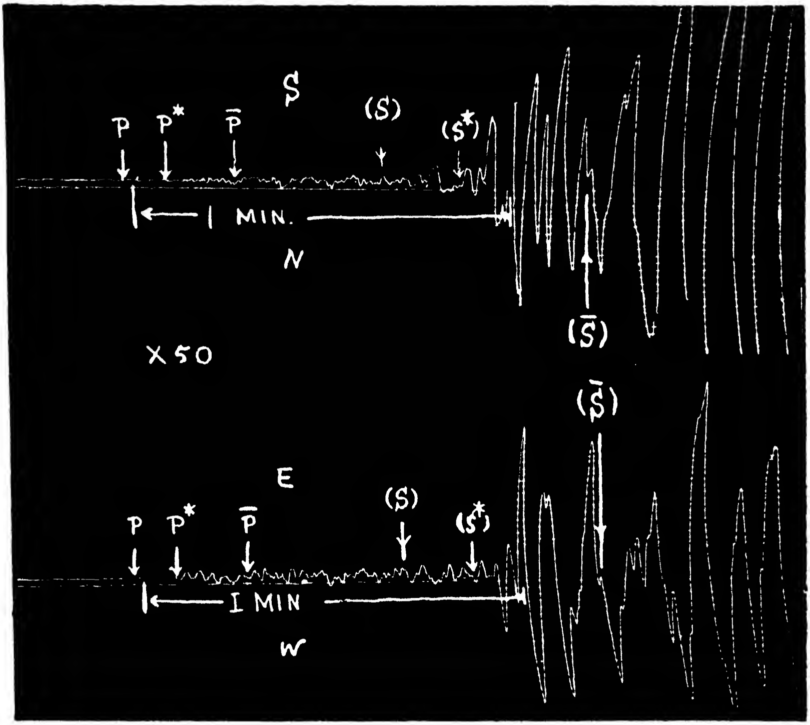


FIG. 40.—Hongo, Tokyo, records for Tango earthquake of 7th March, 1927 (Matuzawa)

over short distances for which the curvature of the earth may be neglected. The values obtained by Jeffreys for European earthquakes are—

P_g	5·57 km./sec.	S_g	3·36 km./sec.
P^*	6·50 „ / „	S^*	3·74 „ / „
P	7·76 „ / „	S	4·36 „ / „

These velocities are greater than the values found for the sedimentary rocks near the surface ; the P_g, S_g values are roughly in agreement with those found for granite, and

P*, S* with those for the basaltic rocks. The normal P and S waves travel at the speeds appropriate for ultrabasic rock such as olivine. The seismological evidence, from the waves shown in near earthquake records, is that the great continental masses consist of two main layers overlying the ultrabasic; these layers are known as the granitic and the basaltic. The upper layer of granite is overlaid by the sedimentary rocks.

It has been found that the time of arrival of any one of the waves at a distance Δ can be expressed in the form $T_0 + d + \frac{\Delta}{v}$, where T_0 is the time of occurrence of the shock at the focus, d is a constant, and v is the velocity; d is known as the "delay of starting" and depends upon the path followed by the waves in travelling through the outer layers. To explain some anomalies in the observations of the European shocks Jeffreys suggested that the disturbance at the focus may only generate transverse waves, and that these waves are transformed into longitudinal waves when they reach the top of the granitic layer. It has subsequently been demonstrated that longitudinal and transverse waves are both generated at the focus of most of the larger earthquakes, but the above hypothesis must still be considered for the very small shocks. According to this hypothesis the paths of the waves from a focus in the granitic layer would be of the type shown in Fig. 41.

The inclinations of the different waves in travelling through the layers can be calculated, since the sines of the angles of incidence are proportional to the velocities. The inclinations corresponding with the velocities given above are—

Waves	*Layer through which waves pass*	*Inclination*
S*	Granitic	64°
S	Granitic	50°
S	Basaltic	59°
P*	Granitic	59°
P	Granitic	46°
P	Basaltic	57°
S_g generating P*	Granitic	31°
S_g generating P	Granitic	26°

The delay of starting for any wave depends upon the velocity, the depth of focus and the thicknesses of the layers. Each passage through a layer of thickness h makes a contribution to the delay which amounts to $\frac{h \cot i}{v}$,[1] i being the inclination and v the velocity of the wave during the horizontal part of its path; the delay is obtained by adding these terms over the whole of the track followed by the waves. Conversely, if the delays of starting for the various waves are given by the observations, it is possible to

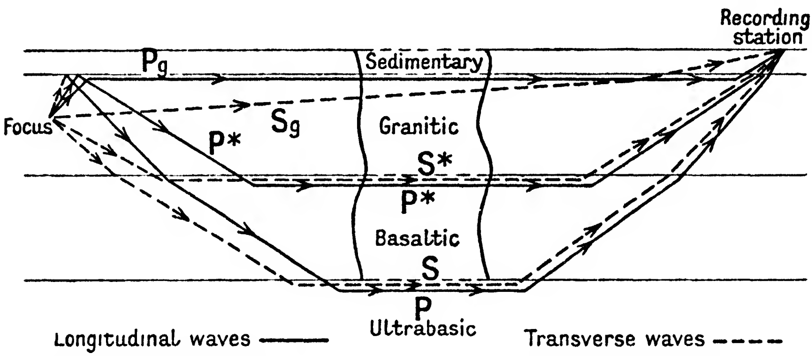


FIG. 41.—Paths of waves, near earthquake with focus in the granitic layer.

calculate the thicknesses of the layers and the depth of focus. Unfortunately errors of a second or two in the delays of starting result in large errors in the thicknesses and the values obtained from different earthquakes are rather inconsistent.

The results obtained from such calculations indicate that the sedimentary layer is generally several kilometres thick, with about 10 km. of granitic rock beneath it, and that beyond the granite there are some 15 km. of intermediate rocks; thus the discontinuity between the crustal layers and the ultrabasic rocks lies about 30 km. from the surface. The properties of the intermediate rocks may possibly vary with the depth, and they may be separated

[1] See page 214.

into several thinner layers. There is evidence that the structure of continental regions in other parts of the world is similar to that in Europe, but there are local variations in the thicknesses of the layers. Very few observations are available for oceanic regions, but it is probable that the total thickness of the layers overlying the ultrabasic rock beneath the oceans is less than beneath the continents.

Fig. 42 shows the Galitzin seismograms obtained at Kew

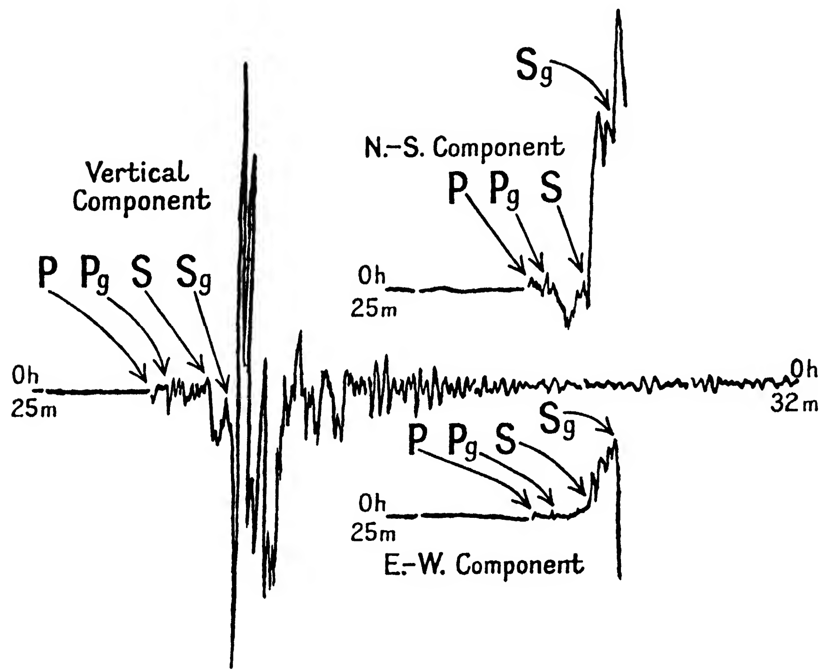


FIG. 42.—Kew records for the North Sea earthquake of 7th June, 1931

Observatory from the North Sea earthquake of 7th June, 1931. The four large onsets in the records indicate the arrivals at Kew of P at 0 h. 26 m. 0 s., of P_g at 26 m. 8 s., of S at 26 m. 30 s. and of S_g at 26 m. 42 s., G.M.T.; the P* and S* waves cannot be identified in these particular records. If we neglect the effects due to the sedimentary layer there is no delay of starting for P_g and S_g, and the observations of these waves give the epicentral distance and time of

origin of the earthquake. The distance, computed from the equation $\frac{\Delta}{3{\cdot}36} - \frac{\Delta}{5{\cdot}57} = 34$, is 290 km. The times taken by P_g and S_g in travelling 290 km. are 52 sec. and 86 sec. respectively, so the time of origin is 0 h. 25 m. 16 s., G.M.T. If the P waves had travelled over the distance of 290 km. at 7·76 km./sec. they would have started from the epicentre at 0 h. 25 m. 23 s., the S waves at 4·36 km./sec. would have started at 0 h. 25 m. 24 s.; the delay of starting is therefore 7 sec. for P and 8 sec. for S. These delays agree with the values obtained by calculation for granitic and basaltic layers of thicknesses 10 km. and 15 km. with the focus 2 km. below the top of the granite. With these assumptions the path of S through the layers consists of

(i) descent at 50° through 8 km. of the upper layer, and ascent through 10 km.,

(ii) descent and ascent at 59° through 15 km. of the lower layer.

The path of P, generated from S_g waves reaching the top of the upper layer, includes

(i) ascent at 26° through 2 km. of the upper layer,

(ii) descent and ascent at 46° through 10 km. of the upper layer,

(iii) descent and ascent at 57° through 15 km. of the lower layer.

Accordingly the calculated delay of starting is

$$\frac{1}{4{\cdot}36}\{18 \cot 50° + 30 \cot 59°\} \text{ or } 8 \text{ sec. for S, and}$$

$$\frac{1}{7{\cdot}76}\{2 \cot 26° + 20 \cot 46° + 30 \cot 57°\} \text{ or } 7 \text{ sec. for P.}$$

Deep Earthquakes

In 1922 Professor Turner called attention to the fact that, although the travel-times of PKP from the majority of earthquakes are consistent, there are some earthquakes for which the waves arrive too early. He suggested that these

early onsets were due to the foci of the earthquakes being situated several hundred kilometres deeper than the average, thereby reducing the distance traversed by the waves in passing through the earth. The hypothesis was not accepted generally for two reasons. In the first place Turner had also suggested the possibility of abnormally shallow foci to account for a few shocks in which the PKP waves apparently arrive late; this implied that the normal focal depth is in the region of 250 km., which is inconsistent with other observations. The difficulties associated with the so-called "shallow" earthquakes have lately been explained by R. Stoneley and E. Tillotson, who found that these earthquakes are composed of two or more successive shocks in the same region, and that the apparent anomalies in the travel-times are due to misidentification of the phases in the records. The second objection to Turner's hypothesis was that some seismologists found it difficult to believe that the changes in the earth's crust, which they regarded as the primary cause of earthquakes, could be effective hundreds of kilometres below the surface.

The existence of "deep focus" earthquakes has been abundantly verified from subsequent work by K. Wadati, F. J. Scrase, R. Stoneley and others. Wadati found in 1928, from observations at small epicentral distances, that the Japanese earthquakes may be classified into two groups. The larger group is of the normal earthquakes; the shocks of the smaller group are felt over a much greater area, and at the epicentre there is an interval of over half a minute between the onsets of the longitudinal and transverse waves, indicating that the foci are exceptionally deep. In 1931 Scrase re-examined the records of some of the supposed deep focus earthquakes to see if they exhibited any peculiarities not shown in the records of normal earthquakes. He noticed that certain phases were shown during the preliminary tremors which do not fit in with the travel times of any of the phases recorded from the normal shocks. Scrase showed that these phases could only be explained as

reflexions of P and S waves near the epicentre; such reflexions may occur in normal earthquakes, but it is only when the focus is deep that these additional phases can be separated from the direct pulses. Stoneley was interested in the reports of surface waves from deep focus earthquakes, for, according to a general reciprocal theorem in dynamics, the surface waves of these earthquakes should be very weak if not completely suppressed; he found that large body waves had often been mistaken for surface waves in the preparation of reports published from different observatories, and that the genuine surface waves from these shocks are very small.

The origin of the supplementary waves can be explained by reference to the simple case of longitudinal or transverse waves reflected once at the surface. For a surface focus reflexion without change of type occurs midway between the epicentre and recording station, but if the focus is deep there are two reflected waves; one corresponds with that from a surface focus and is reflected near the midpoint, the other is reflected near the epicentre, being as it were an echo from the shock. The rays reflected near the focus are denoted as pP and sS. There are supplementary transformed waves sP and pS, and in addition the waves SP and PS have different travel-times for deep shocks and are recorded as separate impulses. The same principles hold for multiple reflexions and for the waves through the earth's core. The travel of some of the simpler waves from a deep focus earthquake to a recording station at a distance of 60° is illustrated in Fig. 43.

The times of travel of the waves from deep earthquakes are now known to a high degree of accuracy. The improvements have resulted from studies by Wadati, Scrase and others of selected deep shocks, and from the investigations of Gutenberg and Richter who have utilized their tables for normal earthquakes to calculate the times for foci at various depths down to 800 km. The travel-times of Gutenberg and Richter for some of the waves from a shock

800 km. deep are plotted in Fig. 44. The wave PKPPKP is one which has been found in the records of deep focus shocks obtained in America from short period seismographs. This wave travels downwards from the focus through the core to the surface and is reflected back through the core to the recording station.

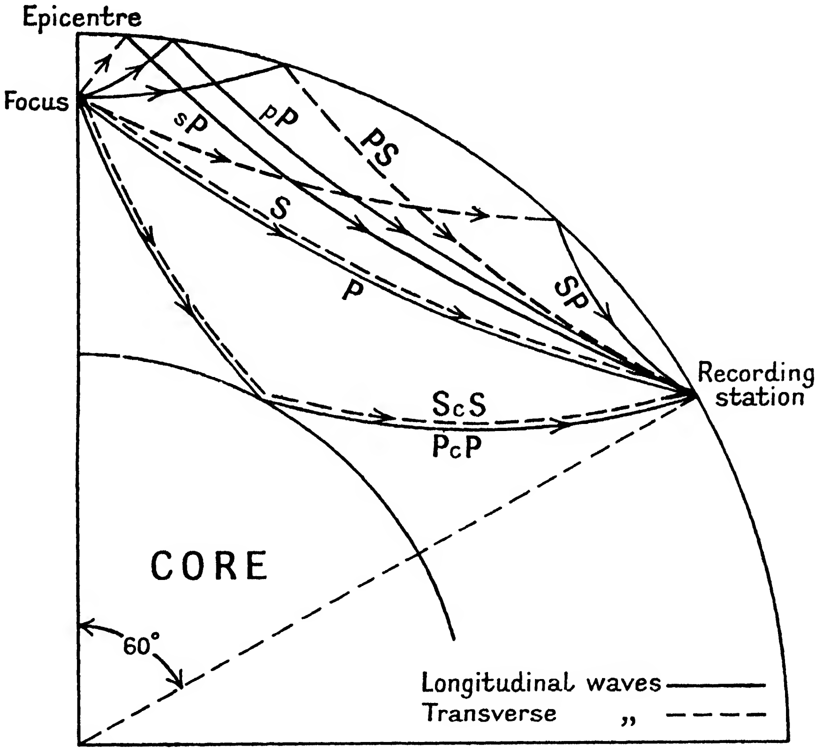


FIG. 43.—Paths of waves from a deep focus earthquake to an epicentral distance of 60°

If the epicentral distance is not too small the travel-times of P and S from a deep focus earthquake are less, and those of pP and sS are greater, than the corresponding times of P and S for a normal earthquake. The mean of the times of P and pP for the deep earthquake may be taken as an approximation for the time of P from the normal one at the same distance. A similar approximation may be made for

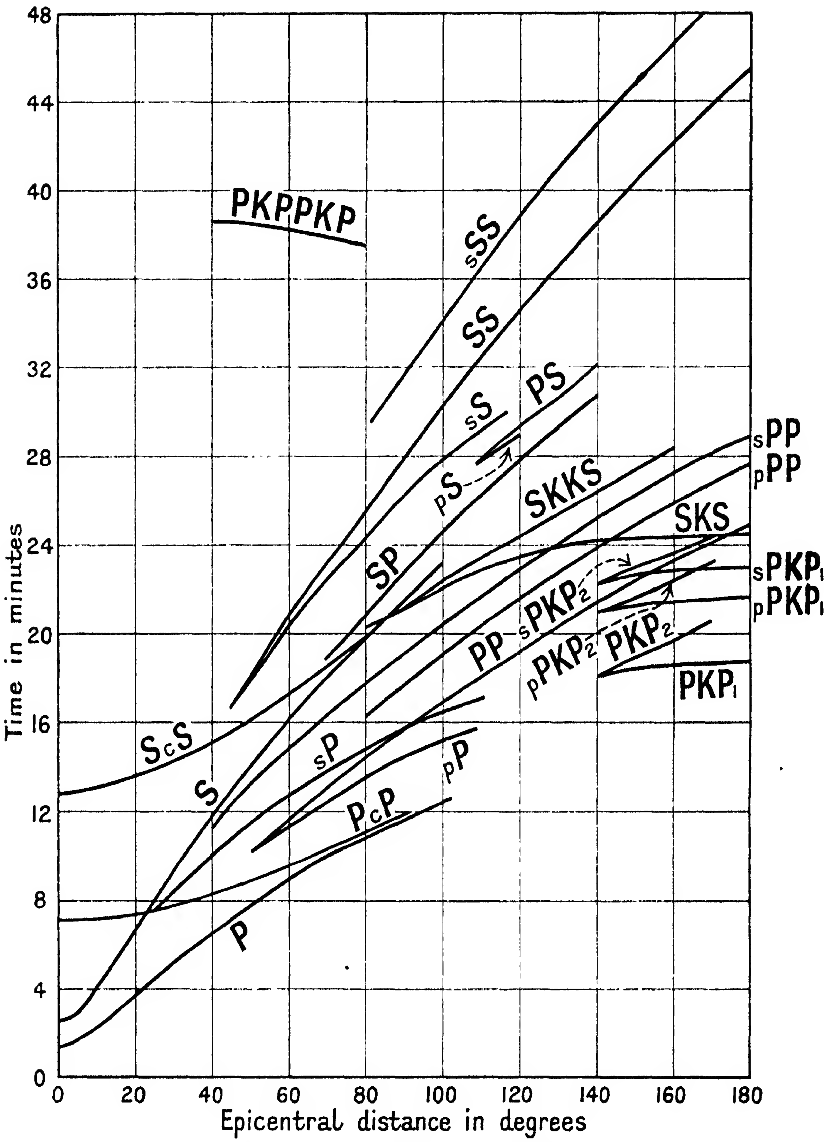


FIG. 44.—Times of travel of waves from an earthquake at a depth of 800 km.

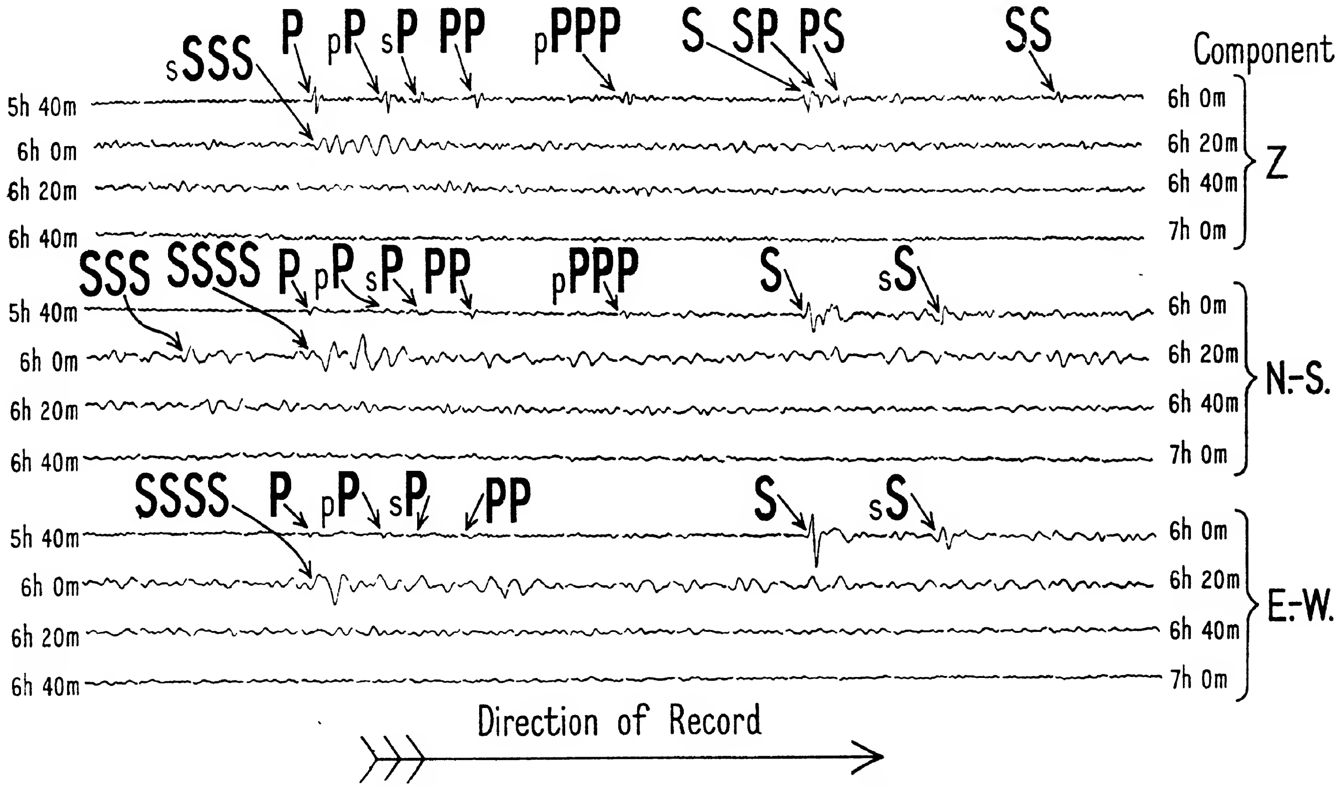


FIG. 45.—Kew records for the deep focus earthquake of 20th February, 1931

the transverse waves. The P and S tables for normal earthquakes can therefore be used for approximate determination of the distance and time of origin from the records of a deep focus shock. The onsets of P, pP, S and sS are selected from the records, and, instead of the S-P interval of the normal shock, we take the interval between the mean of S and sS and the mean of P and pP. The depth of focus is determined from the separation of P and pP and of S and sS.

Some typical deep focus seismograms are shown in Fig. 45. These are records obtained at Kew from the earthquake near the Sea of Japan on 20th February, 1931, which was selected by Scrase for his later investigation. The absence of surface waves from the Kew seismograms is unmistakable evidence of deep focus, and with the supplementary phases clearly shown, Scrase was able, on the day of the earthquake and using the Kew records alone, to locate the epicentre and to determine the depth of focus. The distance of the epicentre from Kew was 8,500 km., the depth of focus 360 km. below the surface, and the time of origin 5 h. 33 m. 26 s., G.M.T. The striking difference between the appearance of the records of deep and normal earthquakes is well illustrated by comparing these records with that for the earthquake on 11th September, 1935 (Fig. 34), which, being near Japan, was at about the same distance from Kew. In the record of the later shock the dominant features are the large surface waves and the onsets of the body waves are comparatively small, but for the deep focus records the body waves are much more prominent and there are practically no indications of surface waves.

Chapter VIII

ANALYSIS OF EARTHQUAKE RECORDS

In studying the records of an earthquake the first essential is to decide whether they are characteristic of a disturbance of normal focal depth, for which the general tables and travel-time curves are appropriate, or whether they represent a very deep shock. The majority of the earthquakes recorded are of the former type. The deep focus earthquakes are easily identified owing to

(i) the absence of surface waves,
(ii) the large amplitudes of the body waves, and the occurrence of the supplementary reflected waves,
(iii) the failure of the phases to accord approximately with the standard diagram of travel-times (Fig. 38).

If the earthquake is not deep the duration of the disturbance, and the time interval between the first movements recorded and the onset of the long waves, are rough indications of the epicentral distance, and we know which of the phases are likely to appear in the records. It must be emphasized, however, that it is frequently very difficult to select the exact instant at which any phase commences, and also that some of the expected phases may not be recorded clearly in the seismograms. When microseisms (see Chapter XIV) are large, the records of an earthquake are so overwhelmed that the recognition of the phases is difficult if not impossible.

Some considerations which assist in identifying the phases shown in the records are summarized in the following notes :

P is the first movement recorded up to a distance of about 105° except within a few degrees of the epicentre.

S appears as a large movement at these distances but is confused around 80° on account of the proximity of SKS.

SKS precedes S at distances greater than 82°, but at distances less than 100° is weak in comparison with the larger onset of S.

PKS first appears near 132°.

PKP appears strongly near 142°.

For distances less than about 35° the derived waves (PS, PPS, etc.) cannot occur and the reflected waves are frequently lost in the later movements of P and S.

Near 60° PP and SS are weak and PPP, SSS may be the first reflected waves clearly showing in the records.

Beyond 80° the direct waves are weaker than the reflected waves; PS and PPS are large.

From 105° to 142° the first distinct pulse is PP, the second PPP or PKS depending on the distance; PS and PPS are large but SKS is less conspicuous than SKKS.

The seismograms for distances greater than 130°–140° are very complicated owing to the large number of phases, and the identifications in most cases can only be arrived at by comparing the times of the movements with the diagram of travel-times.

Information obtained from the Records of a Single Observatory

The epicentral distance and time of origin for earthquakes of normal focal depth are obtained from the time interval between the onsets of P and S if these phases are recorded, except in the case of near shocks when the interval between P_g and S_g is preferable. The distance is usually estimated to the nearest 0·1°, or to the nearest 10 km. For earthquakes at distances too great for P and S to be recorded, and for deep earthquakes, the distance and time of origin may be obtained from the appropriate tables or diagrams of travel-times; an accuracy of 1° or 100 km. in the distance is as good as can be expected.

When the P phase is well recorded the direction of the epicentre can be found by comparing the movements of the

three components. The ratio of corresponding displacements to north and to east gives the direction at the recording station of the great circle passing through station and epicentre. The azimuth, α, of the epicentre from the station can be found from the formula $\tan \alpha = \frac{E}{N}$, where E and N are the amplitudes as recorded by two horizontal seismographs having the same magnification for quick movements ; if the magnifications of the instruments are not the same, the azimuth from north is given by $\alpha = \tan^{-1}\left\{\frac{E}{N}\cdot\frac{V_N}{V_E}\right\}$. The azimuth may be calculated from any prominent movements of the P phase as well as from the onsets, and the method can be applied to the reflected P waves if the movements are clearly shown. The bearing measured from a pair of horizontal instruments is subject to an ambiguity of 180° since $\tan \alpha = \tan (180° + \alpha)$, and we do not know, for example, whether the epicentre is north-east or south-west of the station. The direction of movement in the vertical seismogram shows which of the two directions is correct, for if the initial movement of the ground is upwards the pulse is directed away from the epicentre, and if downwards the pulse is towards the epicentre. Movements outwards from the epicentre are referred to as anaseismic, and those towards the epicentre as kataseismic. The use of the adjectives, anaseismic and kataseismic, to indicate the direction of the movements was advocated by the Rev. E. Gherzi in 1924, and the notation was adopted by the International Seismological Association in 1936.[1]

When the epicentral distance and the azimuth from the recording station to the shock have been determined, the epicentre can be located either by graphical means or by calculation ; the latter method takes a little longer but gives the more accurate results. In the former case the

[1] The term anaseismic, however, had previously been applied by Milne to a shock accompanied by large vertical movements but did not come into general use.

distance and azimuth are set out on a large geographical globe showing the lines of latitude and longitude. The epicentre is the point of intersection between the small circle around the station with the epicentral distance as radius,

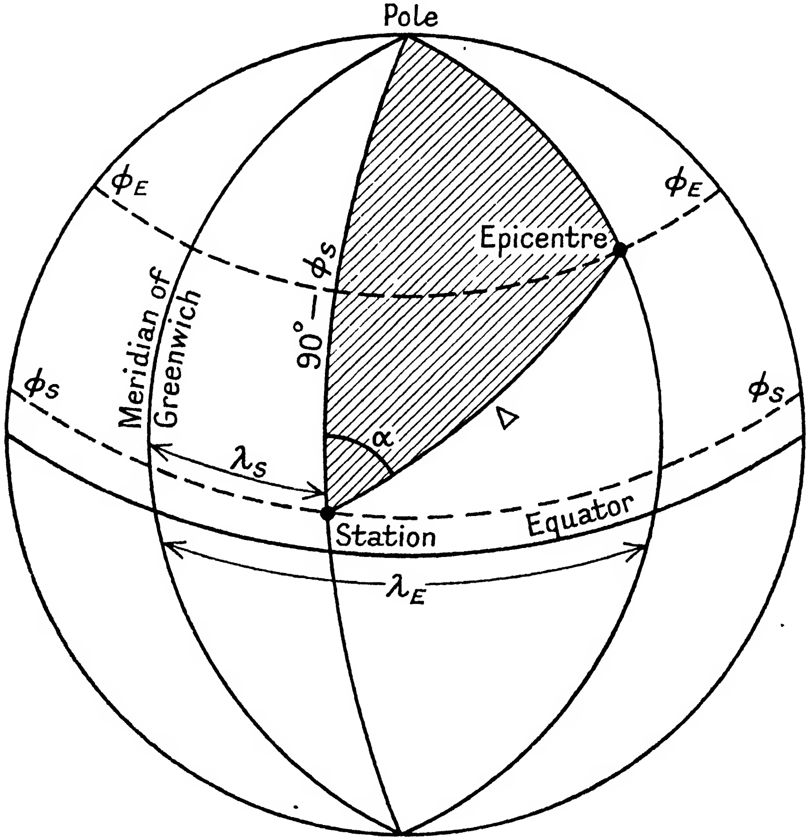


FIG. 46.—Spherical triangle with vertices at station, epicentre and pole

and the great circle passing through the station in the appropriate azimuth.

The position of the epicentre can be calculated from the spherical triangle with vertices at the station, the epicentre and the pole (Fig. 46). In this triangle we know Δ, the epicentral distance, α the azimuth from the station to the epicentre, and ϕ_S, λ_S, the latitude and longitude of the

station. The problem is therefore the well-known case of solution given two sides and the included angle. The latitude of the epicentre, ϕ, and the angle subtended at the pole by the meridians through the station and epicentre, $(\lambda_E - \lambda_S)$, are obtained from the formulæ—

$$\sin \phi_E = \sin \phi_S \cos \Delta + \cos \phi_S \sin \Delta \cos \alpha$$

$$\text{and} \quad \sin (\lambda_E - \lambda_S) = \frac{\sin \Delta \sin \alpha}{\cos \phi_E}.$$

The Kew records of the North Sea earthquake (Fig. 42) provide a good illustration of these methods for determination of the epicentre from the data of a single observatory. The use of these records for finding the epicentral distance and time of origin of the shock has been described on page 107; the values obtained are $\Delta = 290$ km. $= 2{\cdot}6°$ and $T_0 = 0$ h. 25 m. 16 s. The magnitudes of the onsets P and P_g, measured in millimetres from the seismograms, and the directions of the earth movements are—

Vertical component . . .	P 2·7 mm. P_g 8·0 mm.	Ground moving upwards.
N.–S. component . . .	P 1·7 mm. P_g 4·7 mm.	Ground moving to south.
E.–W. component . . .	P 0·7 mm. P_g 1·7 mm.	Ground moving to west.

With the movements to the south between two and three times as large as those to the west, the azimuth is either between north and north-east or between south and south-west; the upward movements of the ground accompanying the displacements to the south and to the west imply that the epicentre is between north and north-east of Kew. It is known from the standardization of the instruments that the magnification of the N.–S. component was 7 per cent greater than that of the E.–W. component, and the azimuths computed from the onsets are $\alpha = 24°$ for P, and $\alpha = 21°$ for P_g. P_g being the larger movement gives the more reliable measurements, so the azimuth may be taken as 22° with a possible error of a degree or two in either direction. On

substitution of the values $\Delta = 2{\cdot}6°$, $\alpha = 22°$, $\phi_s = 51° 28'$ N., $\lambda_s = 0° 19'$ W., in the formulæ on page 118 it is found that the co-ordinates of the epicentre are $53{\cdot}9°$ N., $1{\cdot}3°$ E.

The times of the P onsets from this earthquake at 8 British and 18 Continental observatories are entered on the map of Fig. 47. The circles, representing onset times from 0 h. 25 m. 30 s. to 27 m. 20 s. at intervals of 10 seconds, are drawn around the Kew epicentre. There is excellent agreement between the circles and the observations, showing that the timing and measurement of the seismograms must have been accurate to within a second or two, and that the epicentre is well determined.

Information obtained from the Records of two or more Observatories

The method described in the preceding section for locating the epicentre from the records of a single observatory depends for its success upon the correct identification of the phases, and upon the accuracy of the tables used for finding the distances. During the earlier developments of the subject the tables of travel-times were inaccurate, and it was natural when possible to obtain the epicentres from the azimuths at two or more stations rather than from the distances. On plotting the azimuths for various stations on the globe, it usually happened that the lines did not all run to a point, but gave a number of intersections scattered around the epicentral region; a point, around which the intersections were evenly distributed, would then be selected as the epicentre. There are still advantages in using this method when practicable, for the epicentre found by considerations depending on azimuths alone is as accurate for a deep focus earthquake as for a shock of normal focal depth.

The P phases of most earthquakes are too small for accurate measurements of azimuth, and the distances must be used; fortunately with the better tables of travel-times the distances are known to a high degree of accuracy. The

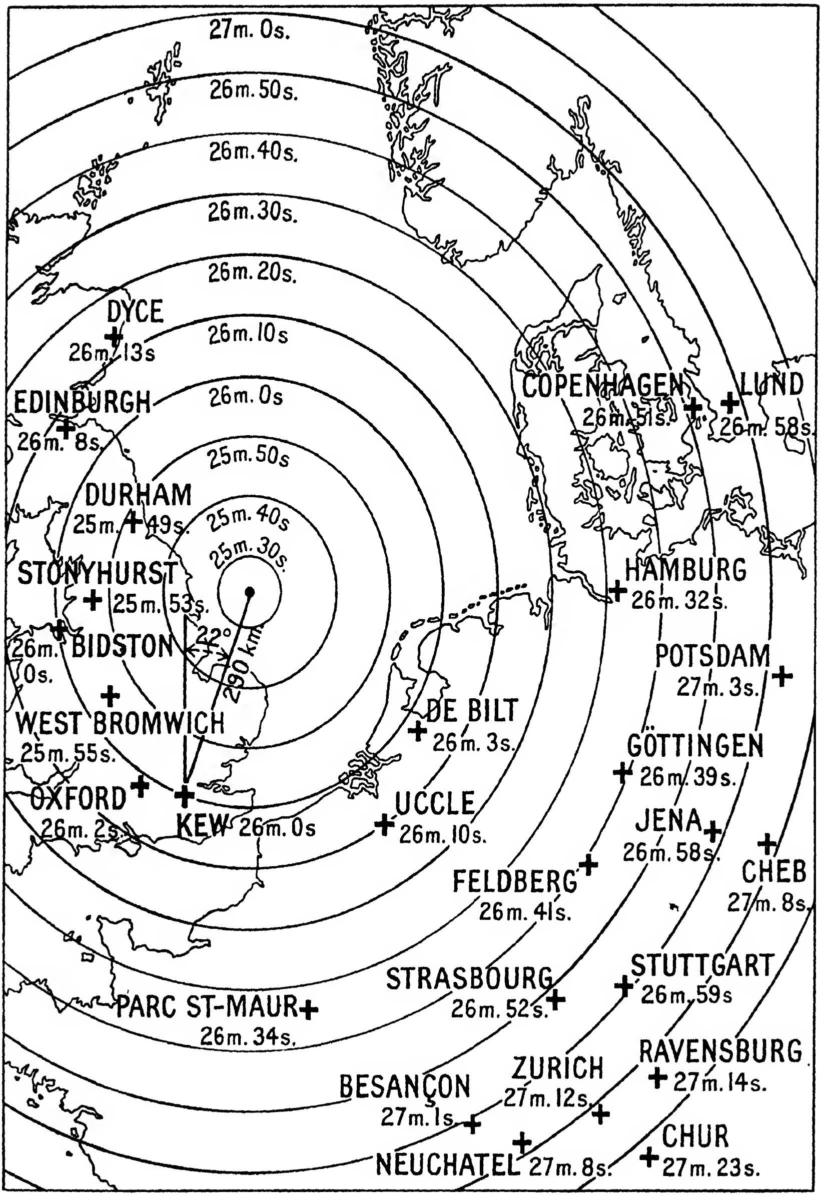


FIG. 47.—Travel of P waves from the North Sea earthquake of 7th June, 1931. (Time of origin—0 h. 25 m. 16 s., G.M.T.)

simplest procedure, knowing the distances from two or more stations, is to draw on the globe a small circle with the epicentral distance as radius around each station. The circles for two stations generally intersect at two points, and further information such as the approximate bearing from one station is needed to discriminate between them in selecting the epicentre; with distances from three or more stations the intersections cluster around the epicentral region.

The epicentre of a large earthquake on 1st February, 1938, was determined at Kew Observatory, using the distances from Kew, Bombay, and Wellington. The onsets identified from the Kew records were:

P	19 h. 19 m. 52 s. (G.M.T.)
PP	24 m. 40 s.
PPP	27 m. 6 s.
SKS	30 m. 22 s.
PS	34 m. 37 s.
PPS	35 m. 51 s.
SS	40 m. 57 s.
L	52 m.

The phases were identified by comparison with the travel-time diagram in the manner described on page 99, and it was found that the earthquake occurred 119° or 13,200 km. from Kew at 19 h. 4 m. 40 s., G.M.T. Information was received that the distances from Bombay and Wellington were 6,800 km. and 6,100 km. respectively, and the epicentre was found by setting out on a globe arcs of circles with the epicentral distances as radii around the three observatories; these arcs are shown in the map of Fig. 48. The common intersection is in the Dutch East Indies near 4° S., 131° E. This epicentre was confirmed from later determinations based upon the data for a large number of observatories.

The epicentre can be determined by calculation if observations are available from a number of stations at several pairs of which the phases are recorded simultaneously. Using the notation given on page 98, let A, B, C be the

direction cosined of the epicentre; then if the phases are recorded simultaneously at two stations, $a_1b_1c_1$ and $a_2b_2c_2$, the epicentre must lie on the line represented by the equation

$$A(a_1 - a_2) + B(b_1 - b_2) + C(c_1 - c_2) = 0;$$

similarly for a second pair of stations with simultaneous

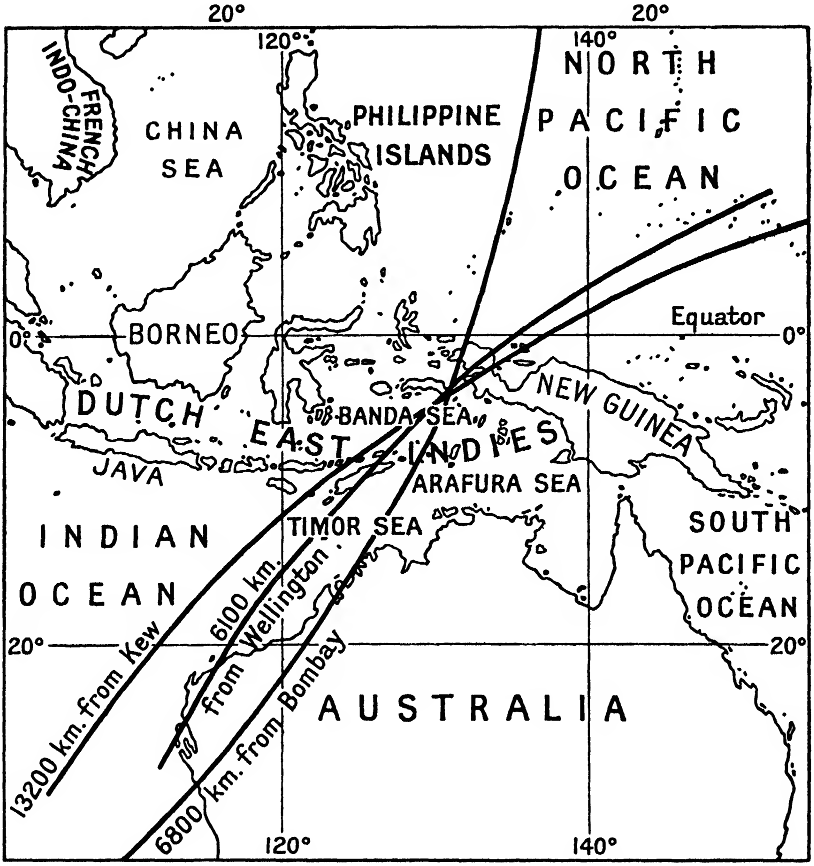


FIG. 48.—Epicentre of Banda Sea earthquake of 1st February, 1938

phases the equation of the line passing through the epicentre is

$$A(a_3 - a_4) + B(b_3 - b_4) + C(c_3 - c_4) = 0.$$

These two equations are soluble for $\frac{B}{C}$ and $\frac{A}{C}$ which give

the geographical co-ordinates of the epicentre. When more than two pairs of stations record the phases simultaneously additional intersections can be computed and the mean position is taken as the epicentre.

This method does not depend upon the travel-times and is therefore well suited for locating the epicentres of deep earthquakes. In his later investigation of the deep focus earthquake of 20th February, 1931, Scrase made a detailed study of the records from a large number of observatories. There were five pairs of stations at which the onsets of P and of S were practically simultaneous: (i) Pasadena and Oxford, (ii) Bidston and Haiwee, (iii) Tucson and Melbourne, (iv) Ksara and Vienna, (v) Kobe and Zinsen. The equations of the loci of points equidistant from the stations in each pair were written out, and the co-ordinates of the intersections were calculated. Intersections at small angles are unsuitable for accurate work and were rejected. The eight intersections used were all between 43° 45′ N. and 44° 39′ N. and between 135° 5′ E. and 135° 58′ E., and the centre of gravity of the eight positions, 44·3° N., 135·5° E., was accepted as the epicentre.

Stereographic Projection

The construction of maps by "projecting" the curved surface of the globe on to a flat sheet dates back to the ancient Greek geographers, and many different projections have been used. It is impossible to represent the surface of a sphere accurately on a plane and the distortion introduced in the map depends on the method of projection; in some cases the areas are approximately correct but the distortion increases towards the edges of the map, in others, such as the well-known Mercator projection, the outlines are nearly correct for equatorial regions but the scale is grossly exaggerated in the higher latitudes. There is one projection, known as "stereographic" which is particularly convenient for use in problems regarding distances and bearings on the globe. The application of this projection

to seismological work was due in 1911 to O. Klotz of Ottawa. The stereographic projection is drawn in the plane of the equator with the pole as the point from which the projection is made. In Fig. 49, *EOE* represents the equatorial diameter of a sphere of radius *R*, and *P* is the centre of projection taken at the south pole. The surface of the sphere is projected on to the plane through *EOE* perpendicular to the plane of the diagram. Any point on the surface is represented on the map at the intersection with the equatorial

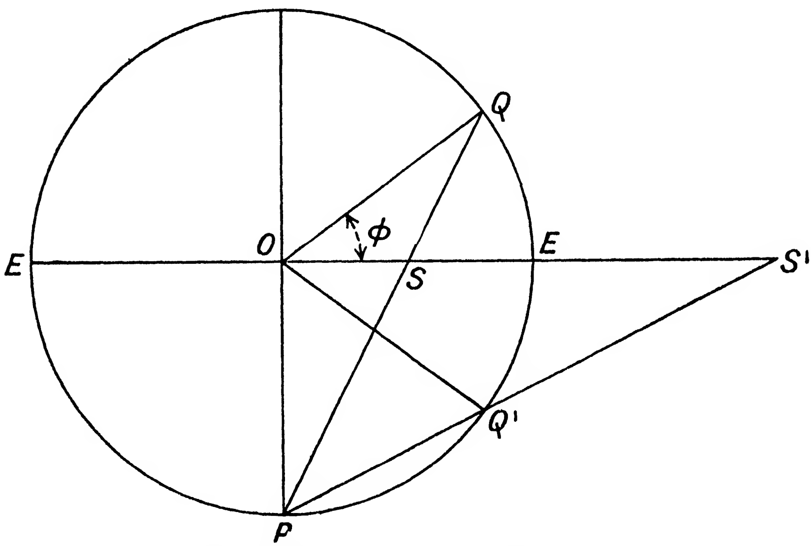


FIG. 49.—Geometry of stereographic projection

plane of the line joining it to the pole of projection. In the map of the world obtained by stereographic projection, Fig. 50, the meridians are represented as lines radiating from the north pole in the centre of the map, and the lines of latitude as concentric circles of which the radii increase with the distance from the north pole. The equator appears as a circle of radius *R*; points in the northern hemisphere are projected inside the equatorial circle, and those in the southern hemisphere outside the circle. The distortion gets worse as the distance from *P* diminishes, and

in the limit the south pole would theoretically be projected as a circle of infinite radius.

The distance from the centre of the map to the position which corresponds with any point on the surface can be calculated from its latitude. Let Q be a point in the northern hemisphere in latitude ϕ, and let S be the projec-

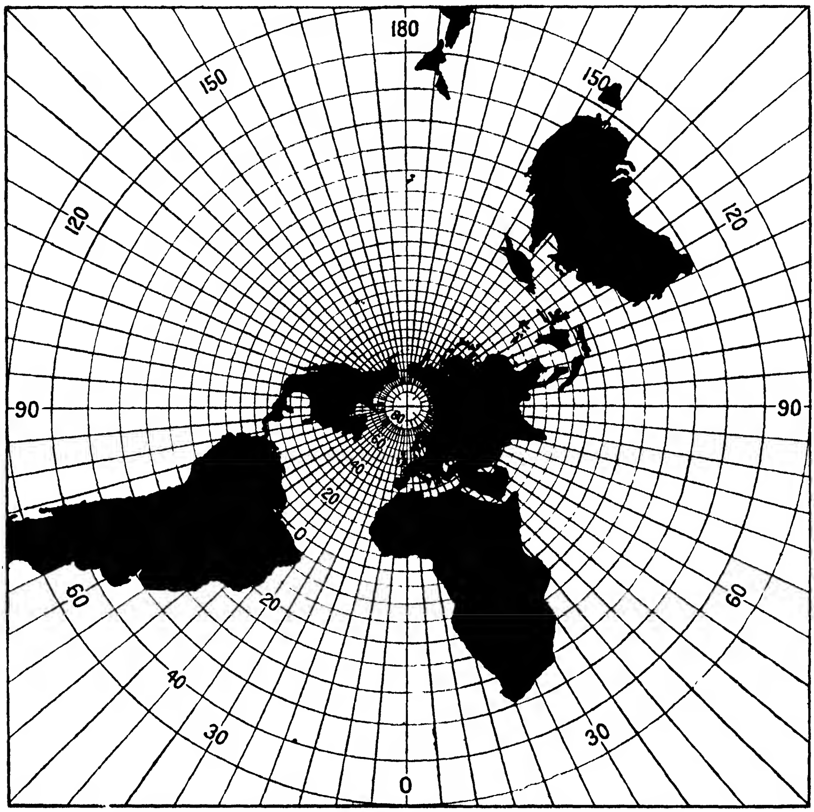


FIG. 50.—Stereographic map of the world (Klotz)

tion of Q on the plane EOE. In the isosceles triangle QOP, $\angle QPO = \frac{1}{2}(90° - \phi)$, and it follows that OS, the distance at which Q is projected from the centre of the map, is $R \tan \frac{1}{2}(90° - \phi)$. Considering next the point Q', in latitude, ϕ' south of the equator and projected at S', we see that $OS' = R \tan \frac{1}{2}(90° + \phi')$. Accordingly if we adopt the

usual convention of regarding the latitude as positive in the northern and negative in the southern hemisphere, the distance from the centre of the map to the projection of any point is $R \tan \frac{1}{2}(90^\circ - \phi)$. A small circle of radius Δ centred in latitude ϕ intersects the meridian in latitudes $\phi \pm \Delta$, and is projected as a circle cutting the meridian at distances $R \tan \frac{1}{2}(90^\circ - \overline{\phi + \Delta})$ and $R \tan \frac{1}{2}(90^\circ - \overline{\phi - \Delta})$ from the centre of the map. The radius of the projected circle, r, and the distance of its centre from the middle of the map, d, are given by the equations—

$$r = \tfrac{1}{2}R \{\tan \tfrac{1}{2}(90^\circ - \overline{\phi - \Delta}) - \tan \tfrac{1}{2}(90^\circ - \overline{\phi + \Delta})\}$$

$$d = \tfrac{1}{2}R \{\tan \tfrac{1}{2}(90^\circ - \overline{\phi - \Delta}) + \tan \tfrac{1}{2}(90^\circ - \overline{\phi + \Delta})\}$$

and may be expressed in the form—

$$r = \frac{R \sin \Delta}{\sin \phi + \cos \Delta}$$

$$d = \frac{R \cos \phi}{\sin \phi + \cos \Delta}$$

The application of the stereographic projection to the location of an epicentre, knowing the distances from several stations, is very straightforward. The values of $\frac{r}{R}$ and $\frac{d}{R}$ for different epicentral distances from the best known seismological observatories have been computed and are available in the form of tables. It is usually convenient to draw the projection to the scale recommended by Klotz in which $R = 10$ cms. Each observing station is represented by a point in the appropriate meridian and distant $\frac{d}{R}$ from the middle of the sheet, and a circle of radius $\frac{r}{R}$ is drawn around this point. The intersection of these circles for a number of stations gives the region of the epicentre.

The earthquake on 1st February, 1938, which according to the measurements of the globe (Fig. 48) occurred near 4° S., 131° E, is an interesting example for the application

of the stereographic projection. The co-ordinates of the three stations, together with the epicentral distances and the values of $\frac{r}{R}$ and $\frac{d}{R}$, are :

Station	ϕ_S	λ_S	Δ	$\frac{r}{R}$	$\frac{d}{R}$
Kew . . .	51° 28′ N.	0° 19′ W.	119°	2·94	2·09
Bombay . .	18° 54′ N.	72° 49′ E.	61°	1·08	1·17
Wellington . .	41° 17′ S.	174° 46′ E.	55°	·66	·61

Fig. 51 is the projection obtained on plotting these values in the manner described above. The common intersection

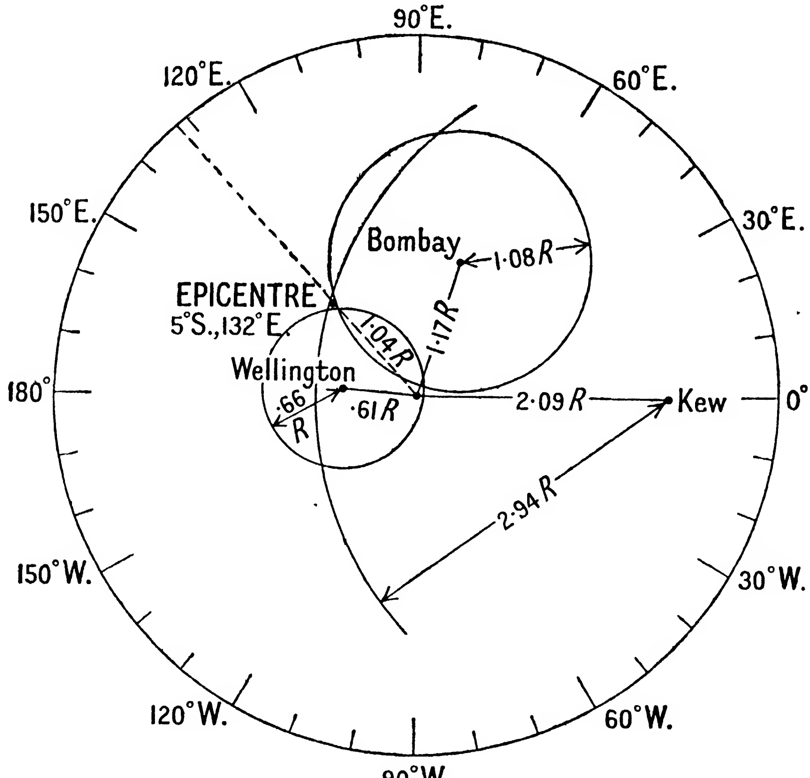


FIG. 51.—Location of epicentre of earthquake on 1st February, 1938 by stereographic projection

of the three circles is in longitude 132° E, at a distance 1·04 R from the centre, and the latitude of the epicentre, found from the equation $\tan \frac{1}{2}(90° - \phi_E) = 1{\cdot}04\ R$, is 4° S. The result obtained by the projection is therefore in good agreement with that given by the measurements of the globe.

Seismic Waves and the Structure of the Earth

We have learnt from the study of the records of earthquakes that the earth is built up of three main portions—there is a central fluid core, about 3,400 km. in radius, surrounded by a rocky shell termed the mantle which extends to within some 30 km. of the surface, and an outer crust. The discontinuity at the boundary of the core was discovered from the records of distant earthquakes, and that at the bottom of the crust from the records of near earthquakes. Our next problem is to consider what further information, regarding the properties of the materials at different depths, can be obtained from the observations of the travel of seismic waves.

From the relation between the travel-times of the waves and the epicentral distance it is possible to calculate the velocities at different depths. The procedure followed for these calculations is known, after its originators, as the Herglotz-Wiechert-Bateman method. It is based upon a mathematical examination of the wave motion in a medium in which the velocity of propagation depends upon the depth. The theory depends upon a number of assumptions, the most important being that the focus of the earthquake is at the surface of a perfect sphere in which the velocity increases continuously with the depth, and that the waves do not travel across any surface of discontinuity. In such a medium it is possible, given the inclination of any wave at the surface, to calculate the depth to which it penetrates and the velocity at the deepest part of the path.

The inclination of the wave which emerges at any epi-

central distance can be determined if we know, v, the velocity near the surface, and $\frac{d\Delta}{dt}$, the apparent velocity over the surface. Let A in Fig. 52 be a point at distance Δ where the wave arriving at the surface is inclined at an angle i to the normal, and let B be an adjacent point at $\Delta + d\Delta$ where the time of arrival is later than that at A by an interval dt. Then, as the wave advances through the distance $d\Delta$ along the surface, it travels from C to B through

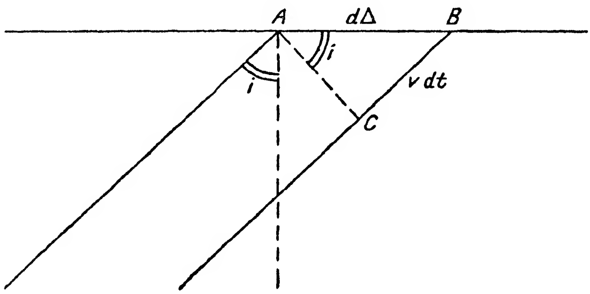


FIG. 52.—Determination of inclination for waves reaching the surface

the distance $v\ dt$, and the inclination is obtained from the relation $\sin i = \frac{BC}{AB} = v \Big/ \frac{d\Delta}{dt}$.

In the application of the Herglotz-Wiechert-Bateman method it is necessary to make allowance for the depth of focus and for the discontinuity at the bottom of the earth's crust. Starting with the time-distance curve for the P waves the procedure is essentially to work out the corresponding curve which would be appropriate if the crust were removed. The time-distance curve for the hypothetical earth without a crust is then taken as the basis for the calculations of the velocity at different depths. Values can be obtained right down to the greatest depths in the mantle of the earth, but the method cannot be applied beyond the boundary of the core for we have no observations which give the velocity immediately beneath it.

It is, however, possible to deduce the times of passage

through the core by comparing the total travel-times of the core waves with those of the corresponding waves reflected off the boundary. To illustrate the principle we may compare the data for PKP with those for P_cP. Let the path of PKP include a distance Δ_1 outside the core and Δ_2 inside, so that the travel-time is equal to the time of P_cP to Δ_1 plus K to Δ_2. Outside the core the path of P_cP to Δ_1 is similar to that of PKP to $\Delta_1 + \Delta_2$ and the angles of emergence of these waves must be equal; this implies that the slopes of the travel-time curves are equal. We therefore work out the slopes over the whole of the ranges of distance covered by PKP and by P_cP, and compare the times and distances for the points at which the slopes of the two curves are equal; this gives the times of K which correspond with various values of Δ_2.

Gutenberg and Richter, taking their tables of travel-times as standard, have calculated the velocities of P and S at different depths in the mantle; for the velocities of K inside the core they used the pairs of waves PKP–P_cP, SKS–S_cS, SKP–S_cP, PKKP–P_cP, and SKKS–S_cS and found good agreement between the velocities obtained from the different combinations, but all the results are liable to some uncertainty near the boundary of the core and near the centre. Their complete results are shown by the curves of Fig. 53. The sharp changes in the velocities, appearing on the left of the diagram, are due to the discontinuity between the crust and the mantle. Just beneath the crust the velocities are about 8 km./sec. for P and 4½ km./sec. for S; these velocities increase to 13½ and 7¼ km./sec. respectively at the boundary of the core 2,900 km. beneath the surface. The velocity of K just inside the core is a little greater than that of S outside it, and increases to about 12 km./sec. at the centre. In the mantle it would be expected that the elasticity and density of the rocks change with the depth, but, since the speeds are greater in the deeper heavier rocks, the changes in the elasticity are more important than those in the density. The changes in the

velocities, as the depth increases, are not uniform. Variations in the rate of increase are most pronounced for depths of about 1,000 km., 1,800 km., and 2,300 km., and it has been suggested that around these depths there are discontinuities in the properties of the rocks.

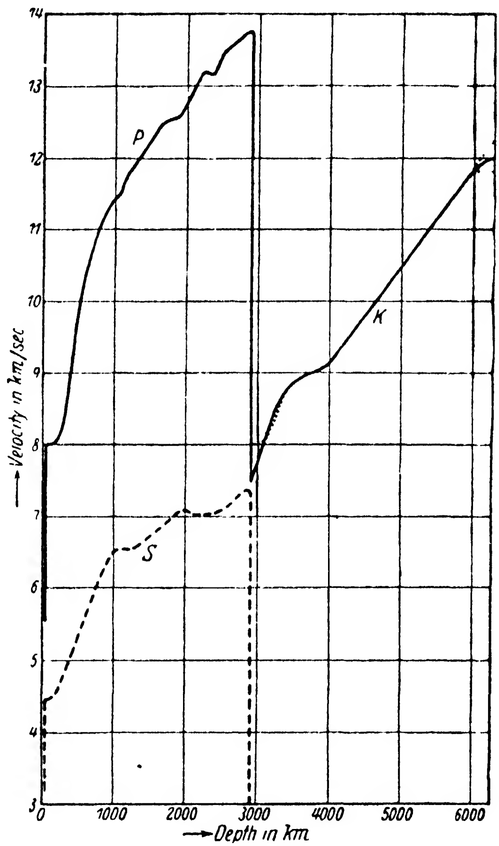


FIG. 53.—Velocities of seismic waves in the interior of the earth (Gutenberg and Richter, 1935)

Some small movements corresponding with the P waves have been noticed in the seismograms obtained at epicentral distances where the P waves are cut off by the shadow of the core. It has been generally believed that these waves are due to the P waves which reach the core being diffracted

and creeping around the boundary. At the greater distances in the shadow zone the diffracted P movements are followed by other waves ; by analogy these later movements have been believed to represent PKP waves which have also been diffracted. The theory of the diffracted P waves is satisfactory but it is difficult to see how the waves of PKP type could be due to diffraction, and other possible explanations of the observations have been examined. A few years ago Miss I. Lehmann showed that the waves, called the diffracted PKP, could be explained as refracted waves if there were a well-marked discontinuity in the velocity of K somewhere inside the core. Following up this suggestion Gutenberg and Richter have worked out a distribution of the velocity inside the core which would be consistent with the observations ; in this distribution the velocity of K increases to about 10·2 km./sec. at a depth of 4,900 km., where there is a rapid increase with depth to 11·4 km./sec. within 300 km., and then a slight decrease to 11·3 km./sec. at the centre. The hypothesis is an interesting one but further confirmation will be required before it can be accepted.

Seismology teaches us something about the properties of the materials inside the earth, but from the seismological results alone we cannot decide what kinds of materials there are at different depths. All we can do is to consider various hypotheses and select the one which is found to be in best agreement with the evidence obtained from seismological or other cognate studies ; among the latter are various geological investigations, determinations of gravity and the density of the earth, and measurements of the small tides in the solid earth which are similar to the ocean tides. Working downwards from the surface the deposition of the sedimentary rocks and their changes are well-known geological processes. The lower rocks in the crust must have been sorted out whilst it was solidifying from a mass of lava, when the more acid granitic rocks being lighter would rise and the heavier basaltic rocks would sink.

There is some doubt about the composition of the lower parts of the crust; the most plausible suggestion seems to be that they are composed of the vitreous basalt known as tachylyte. As we go deeper and penetrate into the mantle the density and the rigidity increase, and the identification of the materials becomes even more speculative. The velocities of the waves just beneath the crust are nearly the same as those obtained from laboratory tests of olivine, and this mineral, in some form or other, is supposed to be the chief constituent of the deeper rocks. Seismology was responsible for the discovery of the core, for the first evidence that it has no rigidity, and for the determination of its size. The average density of the core is found from the value for the whole earth, about 5½ gm./c.c., determined from gravity measurements, and the average value for the rocks in the crust and mantle. The density of the rocky shell is about 4 gm./c.c. so the core must be composed of relatively heavy materials. The density obtained by calculation for the density of the material in the core under the terrific pressures inside the earth is 12 gm./c.c.; it is believed that if the pressure were released the density would be reduced to about 8 gm./c.c., which is about the value for iron. The inference which has been drawn is that the core consists of a heavy metal or mixture of metals. It has been found that nickel and iron are the chief constituents of the meteorites which travel through space and occasionally reach the earth, and it is believed that the core is composed of these metals, probably in a plastic form. The results obtained from measurements of earth-tides provide further evidence that the core has the properties of a fluid. It is found that the rigidity of the earth as a whole, required to explain the observed tides, must be slightly greater than that of steel. The seismological results indicate that the average rigidity for the mantle and crust is much greater than that of steel, and to bring this value into line with the average for core, mantle and crust together, it is found that the rigidity of the core must be negligible.

CHAPTER IX

CATALOGUES OF EARTHQUAKES

THE information available for examination of the distribution of earthquakes in different parts of the world throughout historic times has been collected in many catalogues of earthquakes. The older catalogues, which were prepared from reports found in the histories of various countries, are necessarily incomplete, and do not give a fair representation of the distribution of seismic phenomena over the entire globe. In these catalogues there are uncertainties in the dates, or even the years, for many of the ancient earthquakes. There are numerous inaccurate or obscure references in the original writings, and the dates are frequently given according to some little known system of reckoning. The entries for these ancient shocks refer, for the most part, to widespread disasters. As the material civilization of Europe spread, new countries were settled, printing became common, and records of natural phenomena were more numerous. Small events found a place in history, with the result that in the more recent compilations we find the reports of large and small disturbances side by side. The historical records are fairly comprehensive for civilized countries during the last few centuries, but for uncivilized regions no such records are available; also, many earthquakes which were located beneath the oceans or in uninhabited localities have passed unnoticed. This lack of uniformity in the data has been overcome now that the earthquakes of the whole world are recorded by seismographs. The statistics are complete enough to give a fair representation of the distribution of the earthquakes which now occur, but, since they extend over less than half a

century, are insufficient for showing whether there has been any secular change in the frequency.

Catalogues Prepared from Historical Information

The numerous catalogues of earthquakes may be divided into two groups—(i) regional, and (ii) general or world-wide. Most catalogues in the first group are for regions where earthquakes are frequent, but there are one or two for countries where earthquakes are rare and of small intensity.

About the middle of the nineteenth century, A. Perrey wrote over twenty memoirs about the earthquakes in various countries. The works by F. de Montessus de Ballore, dealing with earthquakes in different regions, appeared about fifty years later; the material from these regional studies was incorporated in de Ballore's great general catalogue to which reference is made below.

Among other catalogues of the earthquakes which have occurred in different parts of Europe, mention may be made of the following:

G. Vivenzio and F. A. Grimaldi, "Italian Earthquakes from the Twelfth to the Eighteenth Centuries."
J. Schmidt, "Earthquakes in South-eastern Europe."
E. Bertrand, "Swiss Earthquakes from A.D. 653 to 1754."
C. Davison, "British Earthquakes from A.D. 974 to 1924."

The last of these is published in Davison's *History of British Earthquakes*, and includes 1,191 shocks.

For regions outside Europe there are catalogues of Japanese earthquakes by Milne and by S. Sekiya, of Chinese earthquakes by P. Hoang, and of American earthquakes by E. S. Holden and others. Hoang's catalogue of Chinese earthquakes covers the remarkable period of 3,662 years, extending from 1767 B.C. to A.D. 1895.

One of the earliest catalogues for the earthquakes of the whole world is that prepared by K. von Hoff; over two thousand shocks from 1606 B.C. to A.D. 1832 are included.

A comprehensive catalogue of between six and seven

thousand earthquakes, prepared by R. Mallet, was published in the *Reports of the British Association* for the years 1852–4. This catalogue, like Hoff's, begins with the year 1606 B.C., which was believed to be the date on which the

FIG. 54 (*a*).—Seismic regions of the world according to Montessus de Ballore. (Western hemisphere)

law was delivered at Mount Sinai (Exodus, Chapter 19). Among other Biblical references it is suggested that earthquakes were responsible for the swallowing up of Korah, Dathan and Abiram (Numbers, Chapter 16), and with the overthrow of the walls of Jericho (Joshua, Chapter 6). Mallet quotes descriptions of earthquakes from many ancient writings, but it is evident that these reports have often been greatly exaggerated. His entries date from the

year 595 B.C. for earthquakes in China, from 285 B.C. for those in Japan, and from A.D. 894 for those in India. The final entry of the catalogue is that for the earthquake in Algiers on 4th December, 1842.

FIG. 54 (*b*).—Seismic regions of the world according to Montessus de Ballore (Eastern hemisphere)

Fernand, comte de Montessus de Ballore, became interested in earthquakes whilst serving as a French officer in San Salvador. He returned to France in 1885, and, from that time, the cataloguing and study of earthquakes became his life-work. He published many memoirs dealing with the seismicity of various countries, and prepared a map (Fig. 54) which is still in some ways the clearest representation of the seismic regions of the world. His greatest

work, however, was never published. This is a monumental catalogue of the earthquakes in all parts of the world since the earliest historic times, and contains information about 171,434 earthquakes. The manuscript is preserved in the library of the Société de Géographie, Paris, where it occupies 26 metres of bookshelves. In 1907 de Ballore went as director of the seismological service which was then being inaugurated in Chile; he spent the remaining fifteen years of his life in that country, organizing the new service, giving courses of lectures about earthquakes in the University of Santiago, and preparing further volumes on seismology which include a bibliography of over 9,000 works.

Milne devoted a good deal of time during several years of his residence at Shide to preparing a *Catalogue of Destructive Earthquakes*, which was published in 1911 in the Report of the Seismological Committee of the British Association. The information, which covers the years A.D. 7 to A.D. 1899, contains excerpts from manuscripts and publications relating to the earthquakes in most countries of the world: 4,151 destructive earthquakes are tabulated in this catalogue, which is of great value in showing the frequencies with which serious earthquakes have occurred in different regions. The intensities of the earthquakes are classified according to three grades:

I. An earthquake of intensity sufficient to crack walls, break chimneys, to shatter old buildings, or to produce cracks in the ground. The radius of the affected area generally does not exceed 5 miles.

II. By an earthquake of this grade of intensity buildings may be unroofed or shattered and some may fall, the ground may be badly cracked in places, and small landslips may occur. The damage extends over an area of radius 20 miles or thereabouts.

III. The highest grade representing an earthquake by which towns are destroyed and districts are devastated. The ground is faulted and fissured, and water, mud, and sand may be ejected from the openings; landslips are common in hilly districts. Damage similar to that of intensity I may occur at distances up to 100 miles.

CATALOGUES BASED UPON INSTRUMENTAL RECORDS

Since seismographs have been installed at observatories in different parts of the world, only very small or local earthquakes can have escaped notice, and for practical purposes the statistics are reasonably complete. Data concerning the earthquakes recorded by the instruments at most observatories are published in monthly or quarterly "seismological bulletins", or in the form of annual summaries. In some cases preliminary information is given in the bulletins, and annual volumes are prepared when fuller information can be included. The latter procedure is adopted in publishing the results obtained from the seismographs at Kew Observatory; bulletins are issued monthly, and the final statistics for each year appear in the *Observatories' Year Book.* Sometimes, where a number of observatories are maintained under the same administration, collective bulletins are issued which include the data for all the observatories in the group. The three most important of these groupings include the observatories of the United Soviet States of Russia, those operating under the United States Coast and Geodetic Survey, and those belonging to the Jesuit Seismological Association which has its headquarters at St. Louis.

It has been mentioned in the Introduction how the data obtained at the different observatories were collected, first by Milne, and later at the University Observatory, Oxford. The earlier information, beginning from 1899, was published in the *Seismological Circulars of the British Association.* The work subsequently has been carried out under the auspices of the International Union of Geodesy and Geophysics, and the *International Seismological Summary* has been published in its present form since 1918. In preparation of the *Summary* the epicentre of each well-recorded earthquake is determined from the times of the P onsets at the different observatories. The data published include the epicentre, time of origin, distances and bearings

for the observatories at which the earthquake was recorded, the times of arrival of the waves, and comparisons between the observed times and those given by the tables. To present the information in a more convenient form Professor Turner prepared catalogues of the epicentres, given in the *Summary* and in the earlier lists, for the years 1913–24. Since Turner's death the work of cataloguing the epicentres has been continued by Miss E. F. Bellamy, and complete lists are available for the period 1913–30. These lists of epicentres are of two kinds, chronological and geographical. In the former are given the dates, times, and the epicentres of the earthquakes, together with the dates of earlier shocks with the same epicentres. Miss Bellamy's *Index Catalogue of Epicentres for 1913–30* incorporates and extends the list published by Turner in 1924, in which the epicentres are listed according to the geographical co-ordinates. The total number of shocks for which epicentres were determined in the 18 years is 6,738. One of the most valuable features of this catalogue is a chart showing the distribution of the epicentres over the globe. This chart, reproduced in Fig. 55, is drawn on the Mollweide equal-area projection of the world. In this projection the surface is represented by an ellipse for which the axes are in the ratio 2 : 1 ; the advantage of the projection is that it gives an accurate representation of the areas of the surface in different latitudes.

CHAPTER X

DISTRIBUTION OF EARTHQUAKES IN SPACE AND TIME

IT is a matter of general knowledge that earthquakes, both great and small, are comparatively common in some regions, and infrequent or unknown in others. An accurate representation of the frequency of earthquakes in the different parts of the globe is necessary for many purposes. We have seen in Chapter IV that, in regions where there are many shocks, the buildings should be of certain types designed to withstand earthquake damage. Again, there are many problems connected with insurance against earthquake risk, and the rates cannot be fixed without information about the seismicity in the regions concerned.

GEOGRAPHICAL DISTRIBUTION OF EARTHQUAKES

The data included in various catalogues of earthquakes have been utilized for the preparation of numerous maps showing the distribution of seismic disturbances over the globe. The best known of the older maps are those prepared by Mallet and by Montessus de Ballore. The first map of earthquake epicentres, determined from instrumental records, was published by Milne in the *Report of the British Association* for 1900. The epicentres of earthquakes in later years were incorporated in other maps by Milne, and more recently in the maps prepared by N. H. Heck and by Miss Bellamy. Some prominent characteristics of the geographical distribution are brought out from all the maps, but even the best of the maps does not give an entirely unbiassed representation of the phenomena. The difficulty arises from the fact that, although there are seismological observa-

tories in most parts of the world, the observatories are more numerous in some regions, such as Japan, Europe, and North America, than in others; on this account the epicentres can be determined for small shocks near the main groups of observatories, whereas similar shocks in other regions are missed. Hence the relative frequencies of earthquakes in Japan, Europe and North America are rather over-estimated.

Mallet concluded that the earthquakes tend to be distributed along broad bands, which generally follow the directions of the mountain ranges near the boundaries between continents and oceans, and pointed out that these mountain ranges indicate the regions of greatest volcanic activity. Montessus de Ballore showed from his map that the earthquakes are clustered along two great belts of seismic activity, one around the Pacific and the other extending from the Alps to the Himalayas; he found that over 90 per cent of the total number of earthquakes lay along these belts, but was careful to point out that the seismicity along the belts is irregular being great in some parts and small in others. Montessus de Ballore attributed this clustering of the earthquakes to instability of the earth's crust along these belts, which are located in regions where the mountain ranges are associated with abnormal crumpling and distortion of the strata.

It will be noticed that practically all the major earthquakes referred to in earlier chapters have been situated near one or other of these two belts, and on inspection of Miss Bellamy's map (Fig. 55), we see that the concentration of earthquakes around these regions is confirmed from the seismograph records of the years 1913 to 1930. On the Asiatic side the belt around the Pacific extends from the Kurile Islands, through Japan, and round the southern coast of China to the East Indies and Polynesia; on the western side of the American continent it follows the direction of the great mountain ranges of the Andes and the Rockies and passes south of Alaska to the Aleutian Islands. The other main belt of seismic activity extends from central

Europe, across the eastern Mediterranean and south-eastern Asia to the Himalayas, and then sweeps southwards through Further India to the Sunda Islands, and merges into the Pacific belt.

Owing to the great sensitivity of the seismographs now in use, many of the earthquakes for which the epicentres are given in the *International Seismological Summary* are of small intensity. It is therefore necessary also to examine the geographical distribution of shocks which are severe enough to cause serious damage. For this purpose we can utilize the data published in the historical catalogues, or that obtained from the seismograms. In either case we encounter a difficulty in specifying what standard must be taken for an earthquake to be regarded as "severe"; no rigid rule can be given for this definition, and the various criteria which have been adopted are necessarily arbitrary.

Davison has examined the historical records as given in Milne's *Catalogue of Destructive Earthquakes*, and has summarized for different regions the numbers of earthquakes during the nineteenth century which were of Milne's grades II and III (p. 138). These numbers are given in the following table.

NUMBERS OF DESTRUCTIVE EARTHQUAKES IN DIFFERENT REGIONS DURING THE NINETEENTH CENTURY (DAVISON)

Philippines	71	Algeria	9
Italy	62	Russia	8
China	59	Russian Turkestan	8
Asia Minor	48	Colombia	7
Japan	42	Ecuador	7
Mexico	42	France	7
Greece	37	Siberia	7
West Indies	29	Sumatra	7
India	27	Austria-Hungary	6
United States	22	Iceland	6
Chile	19	Java	6
Persia	18	Moluccas	6
Spain and Portugal	17	New Zealand	6
Turkey	16	Venezuela	6
Salvador	15	Bolivia	4
Peru	14	Nicaragua	4
Formosa	11	Argentina	3
Alaska	10	Honduras	3
California	10	Costa Rica	2
Guatemala	10	British Isles	0

To allow for the difference in size between these regions Davison divided the number of shocks in each by the area expressed in millions of square miles ; the result, which he termed the " relative seismicity " represents the average number of the destructive earthquakes per million square miles during the century for each of the regions. However, the values of the so-called relative seismicity, calculated in this way, are not suitable for comparisons between the numbers of earthquakes in different regions. The difficulty arises from the fact that the calculated values, being derived from observations of damage to buildings, do not depend solely upon the seismicity, but are influenced by a number of other factors such as the density of population and state of civilization.

As an alternative, if we wish to use instrumental records, the selection of the severe earthquakes can be based upon the size of the earth movements in a given region ; a convenient standard to take is that the amplitude of the earth movement must be at least 0·1 mm. Published data for the amplitudes of the movements recorded by the Galitzin seismographs in Britain are available since 1915. These instruments were in operation at Eskdalemuir Observatory in Scotland until 1925, when they were transferred to Kew Observatory, and the data for the complete period can be used in identifying the regions in which the large earthquakes occurred. During the 23½ years, from the beginning of 1915 to the middle of 1938, the records of these seismographs showed 164 earthquakes which had produced earth movements in Britain with amplitudes exceeding 0·1 mm. The list of the dates and locations of these earthquakes, tabulated in Chapter XVI, pages 232–5, is a convenient summary of the most important disturbances during recent years ; the distribution of the epicentres is shown in the map of Fig. 56. It will be noticed that the North Sea earthquake of 7th June, 1931, and the Belgian earthquake of 11th June, 1938, are shown in this map. The movements recorded at Kew on these occasions, although greater than 0·1 mm., were

of short period, and the records are very different from those of the more distant shocks. In comparison with the other earthquakes these local shocks were slight, and it is debatable whether it would not be better to treat them as exceptional and omit them from the map. Generally speaking the distribution of these larger earthquakes is in very good agreement with that obtained by Miss Bellamy for earthquakes of all degrees of intensity.

The conclusion that the distribution of the severe earthquakes corresponds with that for all the shocks is supported from observations of the earthquakes which are so well recorded at a number of observatories that the epicentres can be determined with more than average precision. An important improvement, introduced into the *International Seismological Summary* from 1930, is a classification of the quality of the epicentral determinations. Each epicentre is indicated as 1 (good), 2 (moderate), 3 (poor) or X (uncertain). The letters N and R precede these characterizations to distinguish between " new " epicentres and " repetitions " from earlier shocks. Excluding the deep focus earthquakes there were 146 shocks with " good " epicentres during the years 1930 and 1931. These are the earthquakes which were used in the investigation of the travel-times of P and S waves, and which formed the basis of the table given on p. 101. The geographical distribution of these earthquakes, which were selected according to the accuracy of the epicentral determinations,. is again very similar to the distribution of all the earthquakes appearing in the *I.S.S.*

Dividing the globe into four regions according to whether the latitude is north or south of the equator and the longitude east or west of Greenwich, the percentages in each region of the 6,738 earthquakes catalogued by Miss Bellamy, together with the average distributions for the 164 severe earthquakes of Fig. 43 and for the 146 earthquakes with good epicentres, are :

Method of Selection	Years	Number of Earthquakes	Percentage of Earthquakes in Region: Lat. N., Long. E.	Lat. N., Long. W.	Lat. S., Long. E.	Lat. S., Long. W.
All epicentres of the *I.S.S.*	1913–30	6,738	60	16	14	10
Movements exceeding 0·1 mm. in Britain . . .	1915–38½	164	59	20	17	4
"Good" epicentres of the *I.S.S.* . .	1930–31	146	67	15	16	2

During the years 1913 to 1931 improvements in the instruments and the opening of new observatories were responsible for a progressive increase in the numbers of epicentres tabulated in the *Summary*. For the two years, 1930–1, there are 1,287 epicentres, and on the average one epicentre in nine is classified as good; the waves recorded at Kew were greater than 0·1 mm. on 24 occasions, such waves being produced from about one in 54 of the earthquakes. Allowing for the facts that the data included in the above tabulation are for different periods of years, and that the seismological observatories are irregularly distributed throughout the world, the distributions of the earthquakes between each of the four regions are in very good agreement. The percentage of good epicentres is higher than the average for the first of the regions which contains the numerous observatories in Europe and in Japan; the epicentres of even small earthquakes within some 20° of these groups can be located accurately, whereas for the last region there are very few observatories and the epicentral determinations are bound to be less reliable.

Mallet pointed out that earthquakes are most prevalent in the regions where volcanic activity is greatest. Small "volcanic" earthquakes, frequently occur in regions around the active or dormant volcanoes; the most important regions in which these shocks are experienced are

around the Pacific, in the Hawaiian Islands, in Italy, in Iceland and around the Caribbean Sea. The connexion between the volcanic and seismic phenomena is not so well marked for the larger earthquakes, although volcanoes and earthquakes are both common near the regions where the stresses in the earth's crust have produced recent folding and crumpling. The epicentres of the larger earthquakes do not generally occur near the volcanoes. In Japan, for example, the volcanoes are situated in the mountainous regions which form the backbone of the main island, where large earthquakes are infrequent. This important characteristic is brought out from the map of epicentres near Japan from 1913 to 1930 (Fig. 57). We see from this map that although earthquakes occur in nearly all parts of the country they are most frequent near the steeper eastern coast which borders the Pacific. It may also be noted that the intensity of the earthquakes near Japan varies in the same way as the frequency, the shocks on the western side of the islands being generally much less severe than those to the east. In other regions we find groups of islands stretching out, like the Japanese, in the shape of a festoon or arc. The Aleutian and the Sunda Islands are typical examples of this formation. For each of these groups the distribution of the epicentres corresponds with that around Japan, the earthquakes being most frequent on the sides of the arcs where the gradients are steepest. Again, in the neighbourhood of the Himalayas, the Rockies, the Andes, and other mountain ranges, earthquakes occur more frequently and with greater violence on the steeper sides. These observations are all evidence of the general law that earthquakes are most frequent in regions where the folding and distortion of the earth's crust is greatest.

In the earlier editions of this work Milne refers to determinations of the slope of the earth's surface along sections perpendicular to the coastlines. The following examples of the slopes, measured over distances of 2°, are typical for seismic and for non-seismic regions.

West coast, South America, near Aconcagua	1 in 20	Seismic regions.
Kurile Islands, from Urup	1 in 20	
Japan, west coast of Nipon	1 in 30	
Sandwich Islands, northwards	1 in 20	
Australia generally	1 in 90	Non-seismic regions.
Scotland from Ben Nevis	1 in 160	
South Norway	1 in 70	
South America, eastwards	1 in 240	

As a result of these determinations Milne concluded that

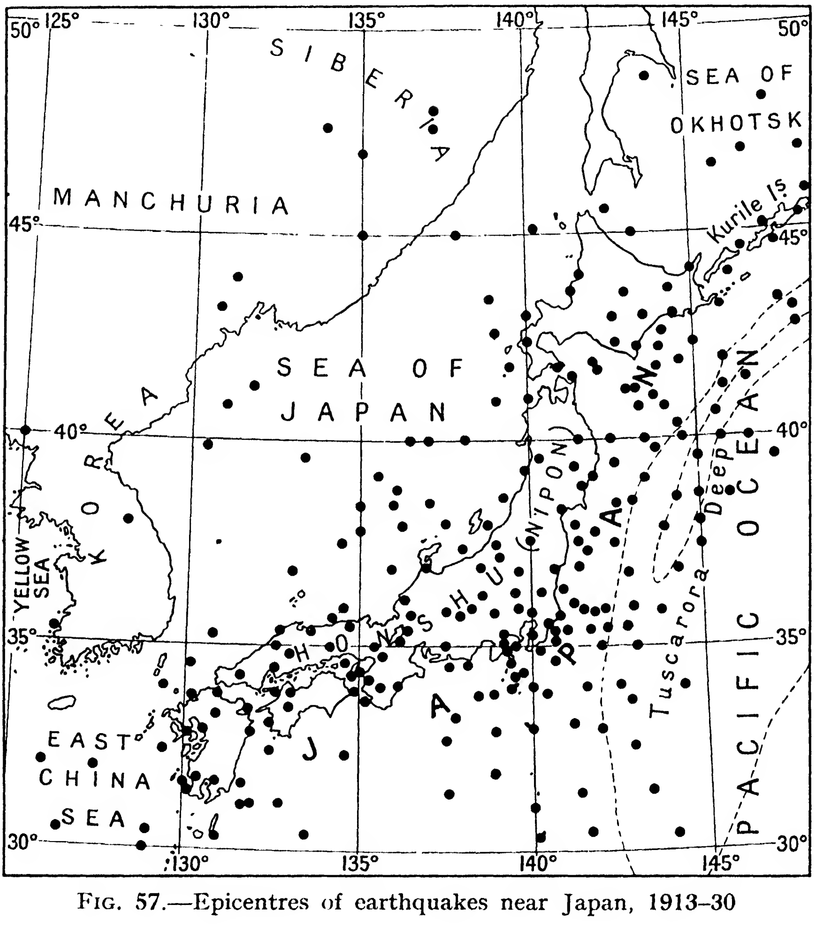


FIG. 57.—Epicentres of earthquakes near Japan, 1913–30

submarine earthquakes may be expected in regions where there are slopes of considerable length extending downwards

beneath the oceans with gradients steeper than about 1 in 35. On the summit of these slopes, whether they terminate in a plateau or as a range of mountains, volcanic action is frequent, whilst the earthquakes originate on the lower portions of the face and base of these declivities. Districts where submarine earthquakes are most frequent are regions like the north-east portion of Japan and the South American coast between Valparaiso and Iquique. The South American trough, which lies within fifty or sixty miles of the coast, and the Tuscarora Deep off Japan, both reach depths of over 4,000 fathoms and are known to be regions in which severe earthquakes frequently occur.

Deep Focus Earthquakes

A map showing the epicentres of the 141 cases of deep focus discussed in the *International Seismological Summary* up to 1927 was published by Turner in the *Summary* for the first quarter of that year. In this map, which appears in Fig. 58, the focal depths are indicated roughly by the size of the dots. Regarding the distribution of these earthquakes Turner writes, " most of them, and especially the deepest, seem to affect the boundary of an oval region about 180° long, centred with fair accuracy on the equator, and including a considerable part of the Pacific Ocean, though its eastern boundary intrudes into South America. The suggestion has more than once been made that the moon came out of the Pacific Ocean ; does this tolerably symmetrical curve indicate the scar which is even not yet quite healed ? " Since this map was published the distributions of the deep earthquakes in various parts of the world have been examined by H. Honda, K. Wadati, V. Conrad, S. W. Visser, H. P. Berlage and others. The most comprehensive investigation, however, is one published by B. Gutenberg and C. F. Richter in 1937.

Gutenberg and Richter catalogued 257 deep focus shocks, selected partly from the information published in the *Sum-*

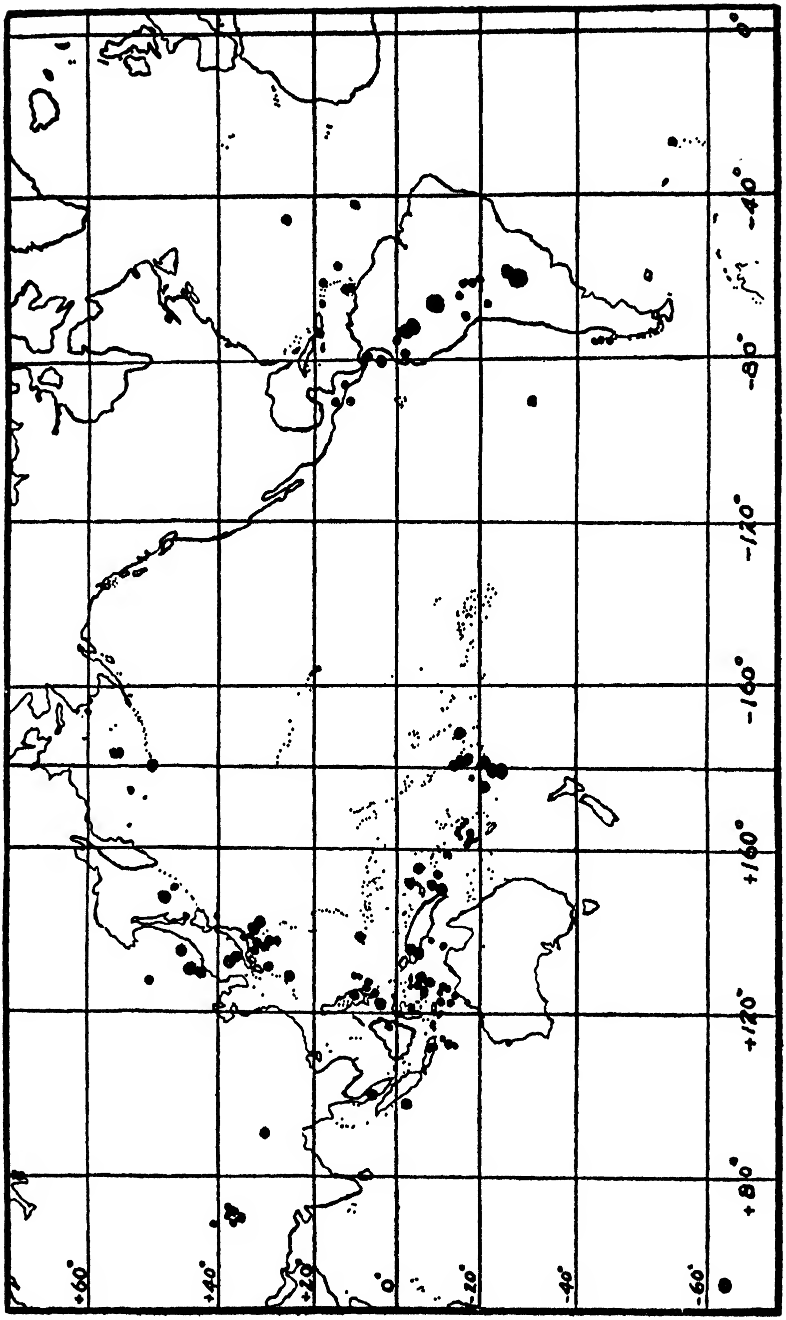


FIG. 58.—Turner's map of deep focus earthquakes up to 1927

mary and partly from other sources such as the bulletins of various observatories. Their catalogue contains practically all the important deep focus earthquakes during the period 1918 to 1931, together with some additional shocks for earlier and later years. To ensure uniformity in the accuracy of the data, the locations of the epicentres, times of origin and depths of focus were recalculated. In the accompanying map of the epicentres (Fig. 59), the focal depths are grouped for the ranges 50–140 km., 150–250 km., 260–490 km., and 500 km. or more. The epicentres of the deeper shocks are confined to five regions—(i) South America, (ii) Japan and vicinity, (iii) East Indies and the Philippines, (iv) New Guinea to New Hebrides, and (v) Regions around Fiji. The shocks at moderate depths are to be found in these regions, along the belt which extends from the Mediterranean across the Himalayas, and also around Central America. In the following table are given the numbers of foci at different depths for each of the five regions mentioned above.

NUMBERS OF FOCI OF DEEP EARTHQUAKES AT VARIOUS DEPTHS (FROM GUTENBERG AND RICHTER)

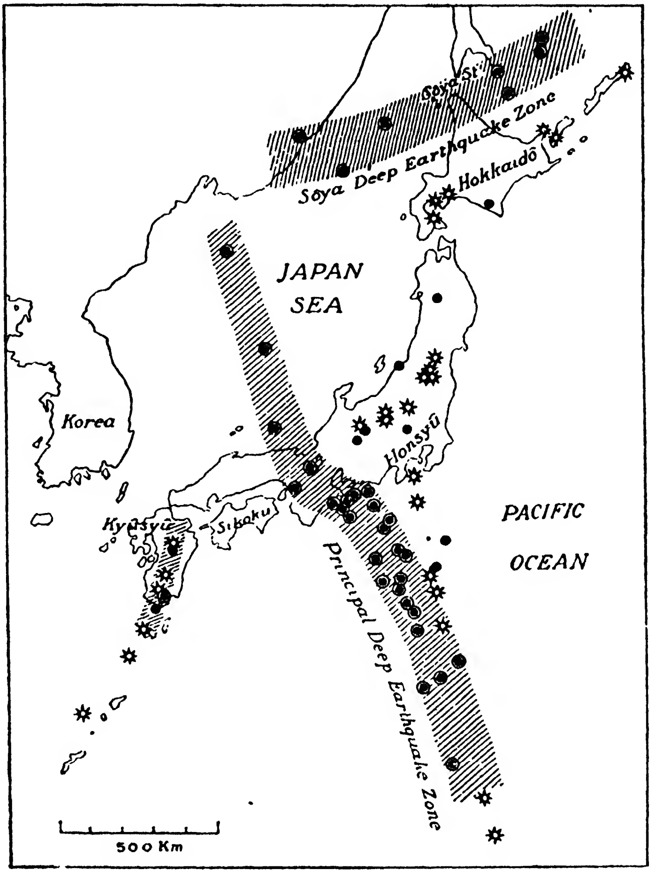
Region	Depth (in km. range ± 25 km.)												
	100	150	200	250	300	350	400	450	500	550	600	650	700
(i) South America .	7	4	6	2	1	—	—	—	—	—	4	9	—
(ii) Japan and vicinity	9	13	6	1	8	16	10	9	5	6	3	1	—
(iii) East Indies and the Philippines . .	6	7	11	3	3	1	3	—	2	—	8	3	2
(iv) New Guinea to New Hebrides . .	6	3	6	1	1	1	3	1	—	—	—	—	—
(v) Regions around Fiji	2	—	2	—	2	1	2	—	3	7	3	1	1

It will be seen from this tabulation that in each of the regions the foci of deep earthquakes are more numerous

around certain depths. These depths are not the same for the different regions. Most of the Japanese deep shocks originate around depths of 150 km. and 350 km.; the very deep shocks of South America are most numerous at about 650 km., those of the East Indies and Philippines at about 600 km., and those in the regions around Fiji at about 550 km.; the deepest focus found in region (iv) is at 450 km. There are 58 shocks with foci at depths exceeding 475 km., 13 in region (i) and 15 in each of the regions (ii), (iii) and (v). The deepest focus on record is that for the earthquake in the Flores Sea on 29th June, 1934, with a focal depth of 720 km.; another earthquake in this locality on 8th August, 1927, had a focal depth of 680 km. The third earthquake which appears in the last column of the tabulation originated south of Fiji on 3rd April, 1931; the focal depth was 680 km.

There is evidence that the deep earthquakes do not occur beneath the localities in which ordinary earthquakes are most frequent. In South America the epicentres of most of the deep shocks lie to the east of the Andes, whereas, although small shocks are common over the whole of the mountainous regions, most of the greater normal earthquakes have their epicentres near the Pacific Coast. The earthquakes of the Malay Archipelago show a similar distribution; those of normal focal depth are most numerous towards the Pacific, and the dominant depth of focus increases from the Pacific to the Asiatic side. Around Japan, where the normal shocks are most numerous on the eastern side of the islands, the deep shocks occur along two belts which run roughly south-east and north-east from Vladivostok; one of these belts crosses the mainland of Japan and extends to the Ogasawara Islands, and the other passes across the Sea of Japan and through the Soya Strait to the Sea of Okhotsk. On the eastern side of Japan these belts pass to the north and to the south of the area around the Tuscarora Deep in which shocks of normal depth are most frequent. The arrangement of the deep earthquakes

along these belts is clearly seen from the maps prepared by Honda and by Wadati (Figs. 60 and 61). Both these maps show that the depths are systematically arranged, being



Volcanoes, active since 1867 ✲✲✲✲✲✲✲✲✲✲✲✲✲✲✲✲✲✲✲✲
Earthquakes of 1927–33 at depths 100–250 km. ●●●●●●
" " " " " exceeding 250 km. ◎◎◎

FIG. 60.—Volcanoes in Japan and zones of deep earthquakes (Honda)

greatest on the continental side of the belts. In Wadati's map the two principal belts of the deep focus earthquakes are joined by lines which serve to emphasize the distribution

of depth. The innermost line indicates the regions of foci at depths of 100 km., the outermost those at depths of 400 km.

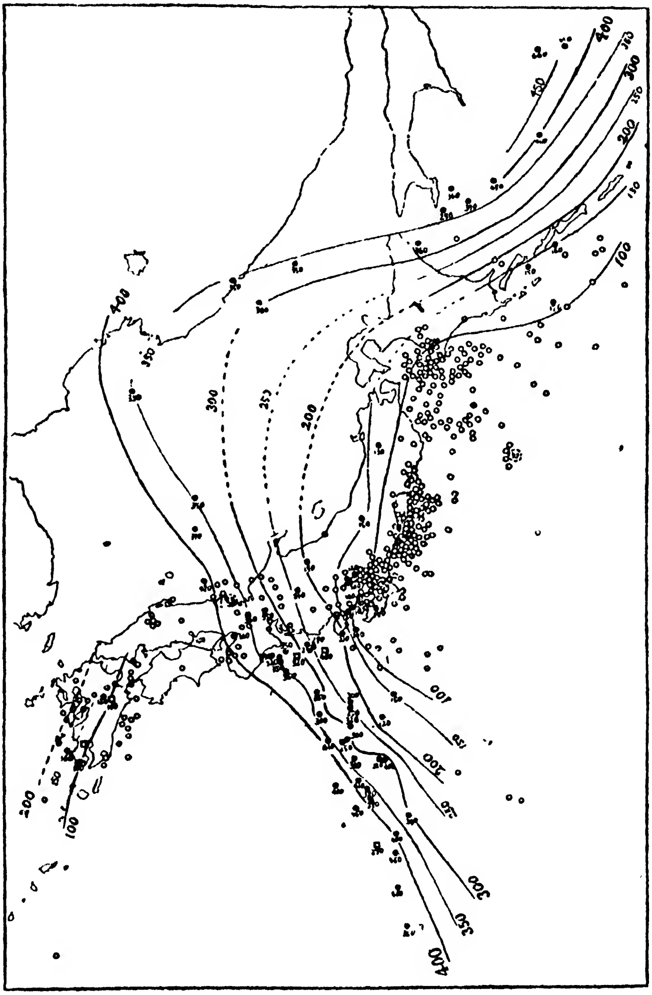


FIG. 61.—Distribution of earthquakes around Japan showing lines of equal focal depth (Wadati)

DISTRIBUTION OF EARTHQUAKES IN TIME

The growth of mountain ranges and the development of the larger surface features show that during the history of

the earth its crust must have undergone great changes. There are numerous observations of large areas which have been raised, and others indicating subsidence. The great mountain ranges are largely formed of sedimentary rocks which have been crumpled and broken by horizontal movements. It is believed that the processes by which these results were produced have been going on for hundreds of millions of years.[1] It is natural to infer that earthquakes are concomitant phenomena with these secular movements which we have reason to believe are slowly going on in certain portions of the earth's crust. If, therefore, we are able by the examination of the rocks which constitute the accessible portions of our globe to determine which periods were characterized by such movements, we may assume that these periods were also periods of seismic activity. Amongst these periods we have those in which various mountain ranges appeared. Thus the Grampians and the mountains of Scandinavia were probably produced before the deposition of the Old Red sandstone. The Urals were upheaved prior to Permian times. The chief upheaval in the Alps took place after Eocene times. The Rigi and other sub-Alpine mountains were formed after the deposition of the Miocene beds. About this same time the Himalayas were upheaved. The fact that earthquakes still occur near these younger mountains indicates that the processes which formed them are still in progress. During the ages earthquakes must have been common in many parts of the world, first appearing in one area and then in another, and in nearly every area we have evidence to show that there have been periods of activity and of repose succeeding each other at intervals of millions of years. In comparison with these long intervals of time the periods included in our histories are insignificant, and there is no indication that seismic activity has increased or diminished appreciably throughout historic times.

[1] See Chapter V of Dr. Jeffreys' book *Earthquakes and Mountains* (Bibliographical reference, No. 25, page 237).

For all parts of the world, except Japan, the historical records of the last few centuries contain many more references to earthquakes than those for earlier times. As Mallet has pointed out, this general increase must have been due to the progress of civilization, which resulted in the records being more complete and embracing greater areas. In Japan, however, there are uniform statistics covering a much longer period, official records of the perceptible earthquakes having been maintained since about A.D. 800. According to Milne's catalogue of Japanese earthquakes the numbers which were recorded during each century from the ninth to the nineteenth are—

Century	No. of Earthquakes	Century	No. of Earthquakes
IX	40	XV	36
X	17	XVI	17
XI	20	XVII	26
XII	18	XVIII	31
XIII	16	XIX	27
XIV	19		

From these figures we see that the numbers during the last two or three centuries have not increased like those for the other regions, and the data support the conclusion that during historic times the amount of seismic activity has not changed to any appreciable extent.

There have been many attempts to find whether the frequency of occurrence of earthquakes depends upon the time of day, the phase of the moon, or the season of the year. The results obtained from these investigations have generally been inconclusive. This is not surprising, since the data are frequently complicated by the inclusion of aftershocks, and the statistical methods employed can only yield definite results if they are applied to a sequence of observations which are entirely independent of each other.

It has frequently been maintained that the aftershocks following a large earthquake occur at intervals which are multiples of 42 minutes. The origin of this belief was a suggestion that, after an earthquake, the rocks near the

epicentre are in an unstable state and may be displaced or fractured by very small disturbances produced by the waves which have been reflected backwards and forwards between the epicentre and the antipodes. Several points of weakness in this hypothesis have been discussed by H. Jeffreys.[1] In the first place the disturbances do not recur at each and every 42-minute interval in the series; secondly, recent work has shown that the travel-time of PKP to the antipodes and back is 40 minutes 24 seconds instead of 42 minutes; thirdly, the phase PKPPKP is a very small movement, and there is no reason to believe that it would be more potent in generating aftershocks than the reflected waves P_cP and S_cS; fourthly, some of the regions in which the material is strained are located at a distance from the epicentre and if aftershocks could be generated in this way they should be stimulated by the direct waves P, S and L. From a thorough investigation of the aftershocks from the Tango earthquake of 7th March, 1927, which was followed by a strong second shock on 1st April, Jeffreys concludes that the aftershocks diminish in frequency with the times after these two earthquakes according to a regular law of chance.

Mallet and other writers have called attention to a number of occasions when large earthquakes have occurred at very nearly the same time in districts separated by great distances. An example of this sort occurred on 19th April, 1902, when shocks originated near Guatemala and in the Indian Ocean, at about 14 hours 21 minutes and 14 hours 34 minutes respectively; the earthquakes were separated by a distance of about 150°. This duplication of earthquake phenomena in different regions seems to be quite fortuitous, arising only from the spasmodic distribution in time of the numerous shocks in different parts of the world.

It has often been suggested that the disturbances in the earth's crust due to a large earthquake may precipitate shocks, termed sympathetic or secondary earthquakes, in other regions. Examples which seem to support such an

[1] Bibliographical reference, No. 26, p. 237.

hypothesis have been mentioned in various works, and the subject was discussed by S. Yamaguti in a paper on "Time and space distribution of earthquakes" in the Bulletin of the Earthquake Research Institute of Tokyo Imperial University, 1933. Yamaguti finds evidence that earthquakes in one part of Japan induce earthquakes in another and makes a similar generalization about the great earthquakes which occur in all parts of the world. The catalogue used in Yamaguti's analysis contained 420 earthquakes which occurred during the years 1900 to 1931. The earthquakes were classified according to the following eight regions :

1. The neighbourhood of the Mediterranean Sea.
2. Continental Asia.
3. Japan.
4. The Philippines and neighbouring oceanic regions.
5. Australia including the oceanic environment.
6. North America.
7. Central America.
8. South America.

Yamaguti compared the proportion of the earthquakes in any region which were succeeded by earthquakes in another region with the ratio to be expected from a fair distribution. For this purpose he determined certain "preferential" ratios according to a rule which may be stated in the following way—Let K and L denote any two of the eight regions, and let $N(k)$, $N(l)$ be the total numbers of the earthquakes in regions K and L respectively ; let N be the grand total, which was actually 420 ; let $N(k,l)$ be the number of cases of an earthquake in region K succeeded by an earthquake in region L. It will be seen that $\frac{N(k,l)}{N(k)}$ represents the proportion of the earthquakes in region K that were succeeded by earthquakes in region L, whilst $\frac{N(l)}{N}$ is the ratio to be expected according to a fair distribution. The preferential ratio for the sequence K,L is defined as $\frac{N(k,l)}{N(k)} \Big/ \frac{N(l)}{N}$.

The preferential ratios determined by Yamaguti are set out in the following table:

S. YAMAGUTI'S TABLE OF PREFERENTIAL RATIOS FOR GREAT EARTHQUAKES IN ALL PARTS OF THE WORLD

		Region of second of the two earthquakes							
		1	2	3	4	5	6	7	8
Region of the first of the two earthquakes	1	1·8	0·4	1·03	1·2	. 1·2	0·37	0·16	0·73
	2	1·3	2·34	1·2	0·63	0·53	0·85	0·37	1·3
	3	0·59	1·0	0·66	1·65	0·53	0·33	1·3	1·64
	4	0·89	0·76	0·83	0·90	1·6	1·0	1·3	0·49
	5	0·94	0·8	0·95	1·1	0·92	1·1	1·15	1·05
	6	0·37	1·7	1·0	1·0	0·54	1·7	1·1	1·3
	7	1·13	0·55	0·58	0·77	1·03	2·2	1·6	0·90
	8	0·73	0·625	1·8	0·74	1·2	0·83	0·90	1·02

Yamaguti believed that there is an enhanced probability of the sequences for which the ratios are greater than unity, and set out a number of conclusions which would be reached if that were the case. The results apparently indicated that in regions 1, 2, 6 and 7, there is a large probability of the occurrence of two great earthquakes in succession; the probability of these repetitions appears to be lowest for Japan. It also seemed that during the last thirty years a notable earthquake in Central Asia tended to be followed by one in South America, whilst the sequence Central Asia–Central America was rare; similarly the sequence Japan–Philippines was apparently common, and the sequence Japan–Australia was rare.

In view of the importance of these generalizations F. J. W. Whipple re-examined the statistics to determine whether the preferential ratios determined by Yamaguti differ so far from unity as to justify the assumption of enhanced probability of certain sequences. He compared the numbers of occurrences of ratios within specified limits with the numbers which would be expected if there were a random distribution of the earthquakes among the eight regions.

The results are graphed in Fig. 62. The abscissæ of this diagram are the preferential ratios and the ordinates are the "integrated frequencies", or the numbers of occurrences of ratios not exceeding specified values. The integrated frequencies obtained from Yamaguti's results are indicated as dots in the diagram ; the values to be expected according to the theory of probability are represented by the stepped graph. Smooth curves have been drawn

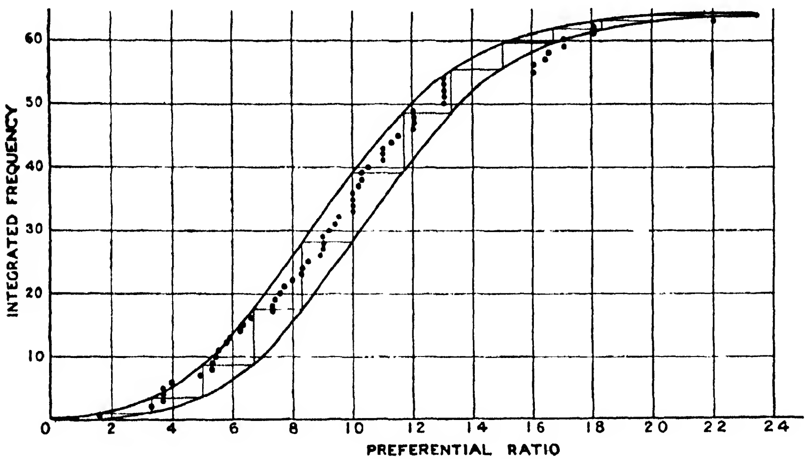


FIG. 62.—Preferential ratios between earthquakes in specified regions and magnitudes of ratios for a random distribution (Whipple)

through the corners of the steps. It will be seen that the great majority of the points representing Yamaguti's statistics are within the area bounded by these curves, and the agreement is good enough to justify the statement that the preferential ratios obtained by Yamaguti are such as would be produced by chance. Hence the zones of the successive great earthquakes are equally likely to occur in any order, and there is no evidence of any systematic tendency in the sequences. Owing to the incidence of aftershocks, however, it is obvious that, unless these shocks are omitted from the data, one is bound to find that successive shocks occur in the same region.

CHAPTER XI

EARLY BELIEFS REGARDING CAUSES OF EARTHQUAKES

SPECULATIONS concerning the causes of earthquakes have been made since the earliest times, and are referred to in the legends and mythologies of many countries. In ancient times earthquakes, volcanic activity, the fossils buried in the rocks, and other things which to the savage have always been unintelligible, were attributed by a few philosophers to natural causes. In the middle ages the teachings respecting such phenomena were that the explanation was only to be found by an appeal to the supernatural, and it was not until the eighteenth century that the educated world, armed with the results of observation, returned to the doctrines of the ancients. Aristotle, Pliny, and other philosophers, whose writings testify to the fact that they had observed steam and other exhalations escaping from volcanic vents, held that earthquakes were due to the workings of wind or imprisoned vapour beneath the earth's crust—a view which finds its parallel in the early philosophy of the Chinese. Natural theories of this order are to be met with until late in the middle ages.

Co-existent with these doctrines are the superstitions that earth shakings are due to the movement of a subterranean god or some mythical monster. In Japan, for example, it was supposed that there existed beneath the ground a large earth spider or "*jishin mushi*", which later in history became a cat-fish. At Kashima, some 60 miles north-east from Tokyo, there is a rock which is said to rest upon the head of this creature and keep it quiet. At this place,

therefore, earthquakes should not be frequent. The rest of the empire is shaken by the wriggling of its tail and body. In Mongolia the earth shaker is a subterranean hog; in India it is a mole; the Mussulmans picture it an elephant; in the Celebes there is a world-supporting hog; while in North America the subterranean creature is a tortoise. The people of Kamtchatka had a god called Tuil, who, like themselves, lived amongst the ice and snow, and when he wanted exercise went out with his dogs. These dogs were, it was supposed, infested by insects, and when now and then they stopped to scratch themselves, their movements produced the shakings called earthquakes. In Scandinavia, which is essentially the land of mythology, there was an evil genius named Loki, who, having killed his brother Baldwin, was bound to a rock, face upwards so that the poison of a serpent should drop on his face. Loki's [illegible] however, intercepted the poison in a vessel, and it was [illegible] when she had to go away to empty the dish that a few drops reached the prostrate deity and caused him to writhe in agony and shake the earth.

In consequence of numerous shocks, which in 1750 were felt throughout Great Britain and were followed five years later by the terrible catastrophe which overtook Lisbon, and because of the general activity of seismic and volcanic agencies which about this time made itself manifest throughout the world, universal interest was attracted to earthquake phenomena. Many of the theories which were then propounded to explain the origin of these mysterious occurrences are embodied in sermons, the authors of which tell us that earthquakes are direct visitations from above, brought about by man's increasing wickedness. In a pamphlet about the earthquake at Palermo in 1706, we read that "the people seemed to be extremely humble and penitent, scourging themselves and doing penance", and in conclusion there is the remark that "it was generally apprehended that this was a mark of God's vengeance for the immorality of the inhabitants". The ideas then prevalent are summed up

in a little poem called " The Earthquake ", written in 1750. It runs as follows:

> What pow'rful hand with force unknown,
> Can these repeated tremblings make ?
> Or do the imprison'd vapours groan ?
> Or do the shores with fabled Tridents shake ?
> Ah no ! the tread of impious feet,
> The conscious earth impatient bears ;
> And shudd'ring with the guilty weight,
> One common grave for her bad race prepares.

The views set forth in the last four lines of this poem still find expression from time to time. After the earthquake which in 1883 alarmed the inhabitants of Charleston, the negro preachers told their congregations that the disturbance had visited that city in particular in consequence of the sins of the people. Again, in 1891, after the great earthquake which devastated Central Japan, evidence of selective providence was found in the fact that a few of the houses tenanted by Christian converts happened to remain standing amongst the ruins of those belonging to their Buddhist and Shinto neighbours. Even in recent years we find an occasion on which an earthquake has been attributed to Divine intervention in the affairs of mankind. According to newspaper reports [1] the Archbishop of Naples declared that the Italian earthquake of 23rd July, 1930, was a visitation from God, provoked by the immodesty of women's dresses and by the immorality of the people. This explanation annoyed many of the victims in the countryside, who asked why, if this was so, Saint Januarius should have intervened to save Naples, whereas the upland villages, to which the Cardinal's remarks did not apply, should have been doomed to destruction.

Among the efforts to explain earthquakes as natural phenomena we find many vague speculations in which they are supposed to be caused by atmospheric disturbances, by electrical discharges, or by chemical changes within the earth. One of the first suggestions that there might be a relationship

[1] Quoted in *The Times*, 28th July, 1930.

between atmospheric disturbances and earthquakes is a quotation given by M. Baratta from Io. B. Portae *De aeris transmutationibus*, 1614, who says:

> "Nihil aliud terraemotus est quam subterraneum tonitruum, et tonitruum est coelestis terraemotus."

Electrical processes are referred to in many writings of the sixteenth and seventeenth centuries; in some of these works it is suggested that electricity, by causing the explosion of subterranean gases, has indirectly resulted in earthquakes, in others the *modus operandi* is not set out. Seismo-chemical theories seem to have had their origin with Vannuccio Biringuccio, who about 1550 wrote ten volumes entitled *Pirotechina*, in which he advanced the idea that earthquake motion was due to some subterranean explosion. Those who, following him, adopted the same idea, endeavoured not only to define the nature of the materials employed in the operation, but the conditions under which they were accumulated in caverns and the method by which they were ignited. Although bitumen and sulphur were thought to have played an important part in the production of explosive gases, the *materia pinguis* or "fatty matter" of Agricola, which by its fermentation gave birth to fossils, was called upon by no less an authority than Des Cartes to produce by similar processes a "fatty vapour" which by its ignition and explosion shook the earth.

The action of water upon quicklime was not neglected, while iron pyrites, as a material yielding sulphurous vapours, was a substance that found favour with many writers. Even as late as 1683 Lyster suggested that earthquakes were more frequent in Italy than in England because the pyrites of the former country might be richer in sulphur than that of the latter, while caverns in which the gases might accumulate were probably most numerous in the most frequently shaken districts.

The ignition of the various gases was attributed to fermentation causing spontaneous combustion, the friction and

impact of falling rocks, the heat developed by combination, and to other causes. Although Lemery in 1703, with a mixture of iron filings, sulphur and water, succeeded in producing the appearances of a volcanic eruption, and like Gassendi, who preceded him, may be accredited with having appealed to experiment to support his views, a little knowledge of chemistry, like a little knowledge of electricity, did much in misdirecting enquiry from its true course.

About the middle of the eighteenth century the idea that earthquakes might in some way or other be connected with volcanic action was revived. Mitchell, writing in 1760, observes that earthquakes chiefly occur in volcanic countries, and suggests that they are the immediate result of steam forcing its way between stratified accumulations in the endeavour to establish an active vent. This view is modified by Rogers, who attributes the pulsatory motion of the surface to the passage of molten lava between the planes of bedding of subjacent rocks.

From this time up to the present many earthquakes have with good reason been attributed to volcanic action. Humboldt tells us in general but vague language that earthquakes and volcanoes result from a common cause, which is "the reaction of the fiery interior of the earth upon its rigid crust". Mallet, who devoted so much time to the study of subterranean phenomena, believed that earthquakes were due to the sudden evolution and condensation of steam. In the concluding chapters of his classical work on the Neapolitan earthquake of 1857 he discusses the effect of water entering heated cavities, where it assumes the spheroidal state and is superheated. On the cessation of these conditions, instantaneous evaporation takes place accompanied by violent explosion. In 1890 a somewhat similar theory was discussed by M. Baratta.

It is now recognized that, although small local shocks may sometimes be attributed to the effects of volcanic activity, the above hypotheses are inapplicable for the ordinary earthquakes, which frequently originate in non-

volcanic regions like the Himalayas. Even in Japan, where there are numerous volcanoes and earthquakes are common, comparatively few of the earthquakes originate in the volcanic regions, the majority of the epicentres being near the eastern coasts of the islands. In addition to this objection to the volcanic theories there is a great contrast between the sizes of the regions affected by volcanoes and by earthquakes; volcanic disturbances are not noticed at distances beyond a few miles from the epicentres, and the disturbed areas are insignificantly small in comparison with the vast regions disturbed by great earthquakes.

Chapter XII

ANASEISMS AND KATASEISMS

In some of the most important researches which have recently been carried out observations of the direction of the ground movements in the regions surrounding an earthquake are utilized to obtain information about the original movements at the focus. The initiative in these investigations was taken by the Japanese seismologists; it may, however, be recalled that even as long ago as in 1848 Mallet had endeavoured to determine whether the vertical component in the waves from earthquakes was upwards or downwards, i.e. whether the movements were anaseismic or kataseismic.

Relation to the Movements at the Focus

In 1905 F. Omori pointed out that at some stations in Japan the movements were generally anaseismic from epicentres in particular regions, and kataseismic from those in others. He assumed that the type of movement was the same in all directions around the epicentre, and suggested that the anaseisms were generated from explosive earthquakes, due to the expansion of gases imprisoned in the earth's crust, and the kataseisms from shocks caused by the collapse of the strata around subterranean cavities.

T. Shida showed in 1909 that the movements due to the earthquake of 21st January, 1906, which originated near the coast of the Boso peninsula some 350 km. south-east of Tokyo, were recorded as anaseisms in some parts of Japan and as kataseisms in others; the anaseisms and kataseisms were separated by a region in which the P

movements were too small to be shown in the seismograms. Realizing that this separation between the initial movements of P in opposite directions depends upon the nature of the disturbance at the focus, he was led to examine the distributions of the movements for a number of earthquakes.

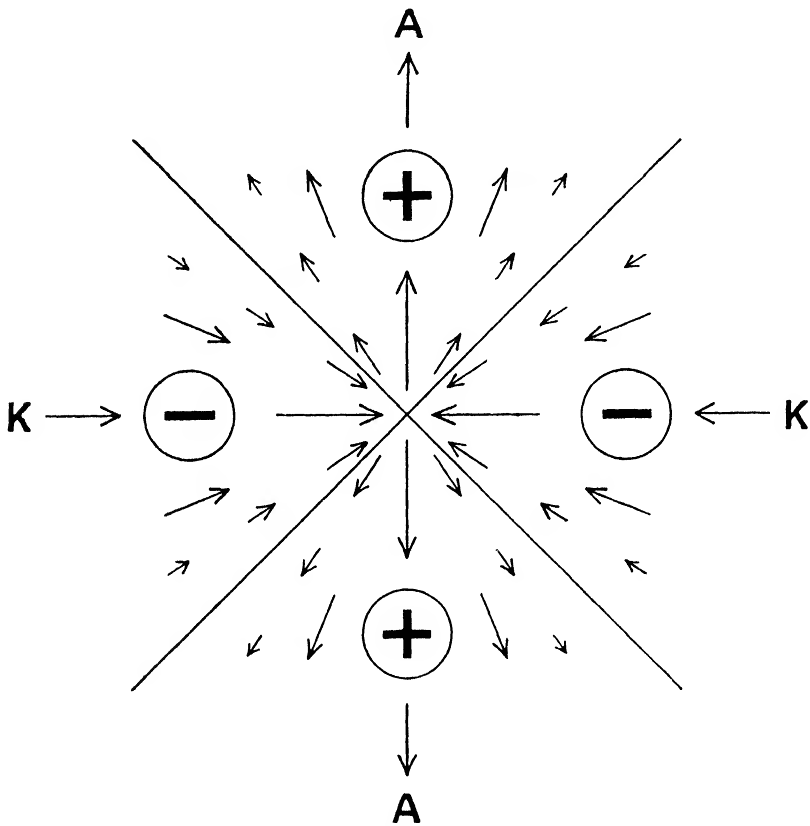


FIG. 63.—Shida's quadrantal distribution of anaseisms and kataseisms

As a result of these investigations it appeared that in the most usual type of distribution, Fig. 63, there are two perpendicular nodal lines which intersect at the epicentre, and the anaseisms and kataseisms are recorded in the alternate quadrants; the amplitudes are greatest midway between the nodal lines, and diminish with increasing distance from

the epicentre. To explain this distribution Shida suggested that a fracture occurs along the direction of the line KK and that the regions on either side of the fracture are forced apart. For some of the earthquakes he studied Shida found a different type of distribution in which the nodal line was circular, with the kataseisms recorded in all azimuths

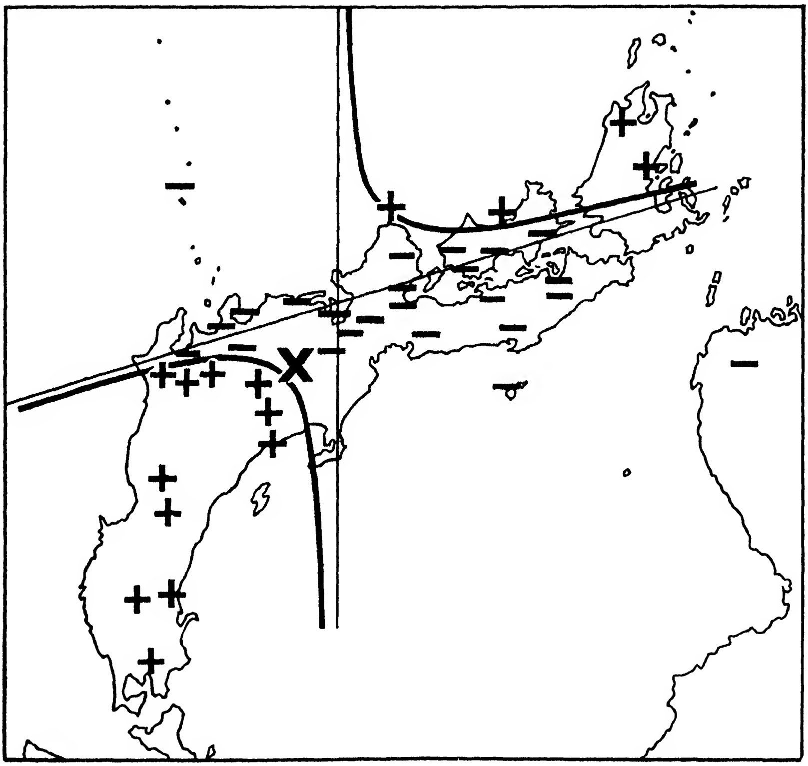


FIG. 64.—Anaseisms and kataseisms from the deep focus earthquake of 2nd June, 1931. Focal depth 240 km. (Tanahasi). Epicentre X

at the smaller epicentral distances, and the anaseisms at the greater distances outside it. He suggested that these shocks were due to the collapse and caving in of large quantities of rock, but it was subsequently shown by Wadati that the kataseisms near the epicentre are the onsets of P_g, whilst the anaseisms are onsets of waves which have pene-

trated deeper than the granite and which arrive later than P_g at the smaller distances.

Following the demonstration that the anaseisms and kataseisms are regularly distributed, S. T. Nakamura and other Japanese seismologists studied the distributions for a number of earthquakes. Nakamura found a close connexion between the nodal lines and the tectonic features around the epicentre, and, as an alternative to Shida's hypothesis, attributed the distribution into quadrants to movements of the rocks along a fault in one of the nodal planes.

An important discovery was made in 1931 by K. Tanahasi, who found from a study of the movements recorded from the deep focus earthquake in the central part of Japan on 2nd June, 1931, that in the distribution of anaseisms and kataseisms the nodal lines are hyperbolas. The map for this earthquake is shown in Fig. 64. M. Ishimoto realized that Tanahasi had discovered a new class of phenomena; he examined other abnormal distributions and found that the nodal lines at the surface were all conic sections. To explain these distributions Ishimoto assumed that the original disturbance is composed of two couples, and that the surface of separation between movements in opposite directions is in the shape of a cone with its apex at the focus. According to this hypothesis the movements are anaseismic everywhere inside the cone and kataseismic outside it. The mechanism producing hyperbolic and elliptic nodal lines is illustrated in Fig. 65. The nodal cones, containing the anaseismic movements, are shaded in the vertical sections at the bottom of the figure, and vertical displacements of the surface are indicated by broken lines. The left-hand side of the figure shows the cone with its axis horizontal, and the intersection of the surface with the nodal cone occurs along the two branches of an hyperbola; the axis of the cone on the right is inclined slightly to the vertical, and at the surface the nodal line takes the form of an ellipse. Ishimoto suggested that the earthquakes giving these new distributions of the nodal lines

are due to an accumulation of molten rock around the focus bursting through the surroundings which yield in their weakest direction ; this latter direction is the axis of the nodal cone.

The more recent developments have followed theoretical lines. Many hypothetical systems of forces at the focus have been examined, and the distributions which they give

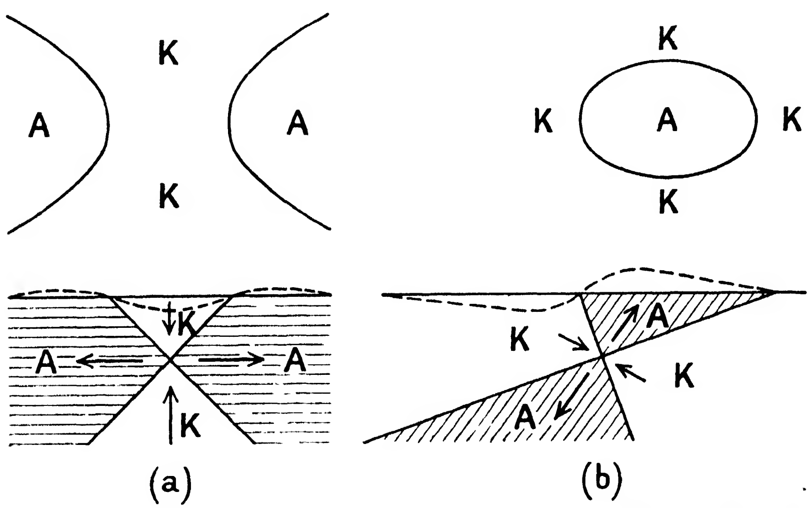


FIG. 65.—Distribution of anaseisms and kataseisms with a nodal cone through the focus (Ishimoto)

for the amplitudes of P and other waves have been compared with the observations. Some of these mathematical investigations have given very interesting results ; in others the results are not conclusive. In the former category may be mentioned the studies by H. Honda and T. Miura, who discussed the distribution of strain in a solid subject to forces applied to the boundary plane, and by F. J. W. Whipple, who worked out the corresponding distribution for the stresses associated with internal strains. This latter investigation refers to internal strain of the type giving anaseisms and kataseisms in alternate quadrants. The resulting horizontal and vertical displacements are illustrated in Fig. 66. In this diagram the direction and the relative magnitude

of the horizontal displacement are indicated by the arrows. The vertical displacement is upwards wherever the radial displacement is outwards, except beyond the circle where the vertical displacement is reversed. The inner curves bound the areas in which the vertical displacement exceeds a quarter of its maximum value.

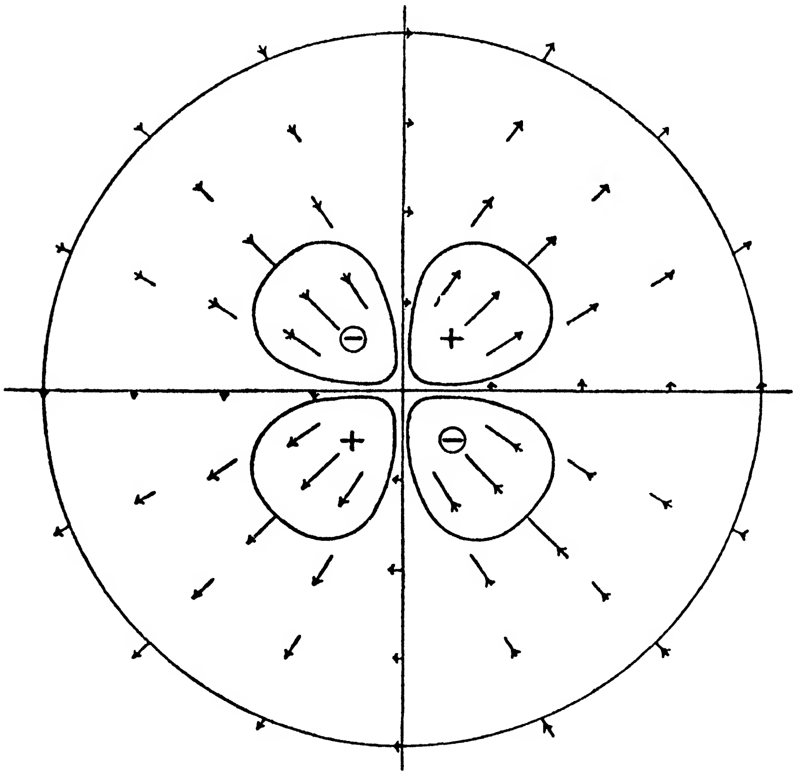


FIG. 66.—Movements of a solid around a region of internal strain (Whipple)

Regarding the applicability of the diagram to the observations of earthquake waves, Dr. Whipple remarks [1] that :

> In considering the relation of the theory to the phenomena of earthquakes we assume that the rocks are subject to stresses

[1] Royal Astronomical Society, *Monthly Notices*, Geophysical Supplement, Vol. 3, 1936, pp. 387–8.

under which fracture or slipping eventually occurs at a certain point, the focus. The surrounding rocks accommodate themselves to the new position of the rocks near the focus. The movements must be analogous to those which would be produced by the annihilation of the hypothetical nucleus of strain.

It is to be noted, however, that, whereas in the theory the elastic limits are not exceeded, in practice fractures occur. It may be that the fractures are in some cases confined to surface rocks, which are much weaker than the deeper ones.

For comparison with the theory a critical examination of the observations of changes of level and of the horizontal displacement produced by earthquakes in various parts of the world is desirable. Some of the instances cited by Honda and Miura are in fair agreement with the results of the calculations in the present paper, but I am not certain whether their diagrams are to be regarded as largely hypothetical or as representations of adequate surveys.

It has been demonstrated from the investigations referred to in the preceding paragraphs that the stresses which produce the movements at the focus are of definite type, and that they operate in specific directions. It is, however, no easy matter to ascertain the exact nature of the mechanism which produces the movements in any particular earthquake. The theoretical results only apply for a uniform medium, whereas the rocks in the earth's crust are of variable composition and there are many irregularities in their distribution ; a further difficulty arises since the forces causing the displacements are generally very complicated, and the planes in which they operate may be inclined at any angle between the vertical and the horizontal. The results so far achieved have thrown new light upon this difficult problem but it is obvious that many more earthquakes will have to be studied before we can obtain a satisfactory representation of the processes involved.

Distributions for Individual Earthquakes

The concentration of the anaseisms in some regions and of kataseisms in others is not confined to the districts sur-

rounding the epicentre. Regular distributions have been found for the movements recorded in all parts of the world from some great earthquakes. One of the first investigations of this kind was carried out by P. Byerly who investigated the travel of waves from the Montana earthquake of 28th June, 1925. He found that the initial movements were anaseismic within a sector of between 60° and 105° towards the north from the epicentre, and kataseismic in the other directions for which seismograms were available. Subsequently Byerly discussed the observations for the Chilean earthquake of 11th November, 1922, and the Texas earthquake of 16th August, 1931; for each of these earthquakes, even at great distances from the epicentre, the observations generally showed anaseisms in some directions and kataseisms in others.

Gutenberg and Richter examined the onsets of P in different parts of the world from two large earthquakes which occurred near the south coast of Sumatra on 10th February and 25th September, 1931, and which had been included in the shocks utilized for their investigations of travel-times. At all observatories for which comparisons could be made it was found that the initial movements for the latter earthquake were in the same direction as those for the earlier one. The observations are not very numerous and there were no conspicuous groupings of anaseisms and kataseisms for these shocks. The map published by Gutenberg and Richter shows in Europe 10 anaseisms and 8 kataseisms, which appear to be scattered at random; possibly this irregularity is due to a nodal line passing among the European observatories.

Fig. 67 shows the types of initial movements recorded from the deep focus earthquake near the coast of Siberia on 20th February, 1931, which was the subject of Scrase's investigation. In the map anaseisms and kataseisms are represented by the signs + and − respectively. At Kew the onset was kataseismic, the ground moving to the north, to the east and downwards. There were movements of this type at all the

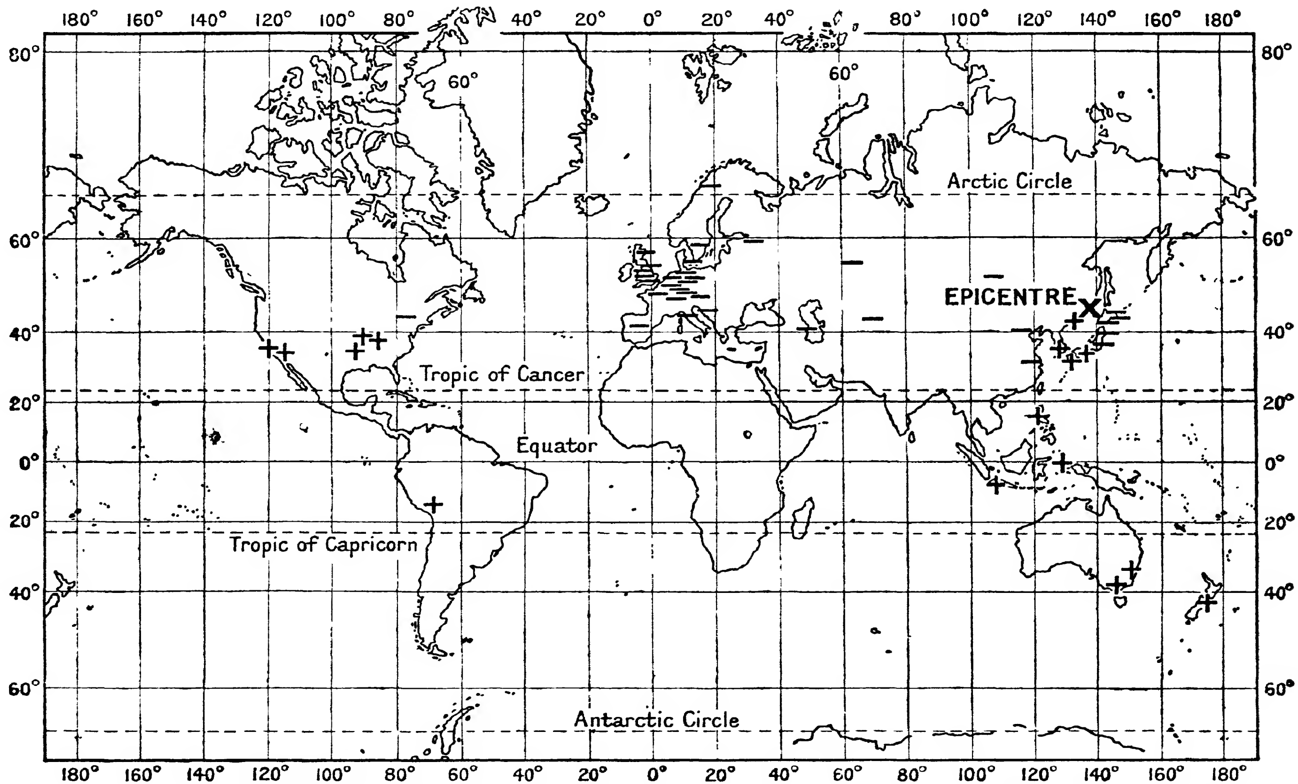


FIG. 67.—Distribution of initial movements from the deep focus earthquake of 20th February, 1931

observatories in Europe, in central Asia and in China, and again in Japan to the south-east of the epicentre. Anaseisms were recorded at most of the American observatories, at Vladivostok, and to the south of the epicentre in regions which include the East Indies, Australia and New Zealand. The observations illustrated in Fig. 67 are more consistent than those obtained previously for earthquakes of normal focal depth. This would have been expected since the body waves are much larger for deep than for normal earthquakes, and there is therefore less uncertainty in the observations of the direction of the initial movements. Frequently for normal earthquakes the initial movement is very small and followed several seconds later by a sharper movement. An *e* phase due to the genuine P waves is followed by a larger *i* phase, the latter probably being the onset of *s*P. At some stations, especially at those with only one horizontal seismograph, the *e*P is likely to be missed, and if not missed altogether the sign of the initial movement may be doubtful owing to the occurrence of microseisms.

Statistical Results

Omori's suggestion that the initial movements at a given observatory are generally anaseismic for earthquakes in some regions, and kataseismic for those in others, has been verified from the observations in other parts of the world. In the following table are given the numbers of occasions on which anaseismic and kataseismic waves from different parts of the globe reached the observatories of Kew and Uccle in north-western Europe, Sverdlovsk in central Asia, Pasadena in California, Zi-Ka-Wei in China, and Riverview in New South Wales.

Region of Epicentre	Kew 1926–37		Uccle 1911–28		Sverdlovsk 1922–7		Pasadena 1931–4		Zi-Ka-Wei 1922–8		Riverview 1913–24	
	A.	K.	A.	K.	A.	K.	A.	K.	A.	K.	A.	K.
Southern Europe and Mediterranean . .	17	21	10	36	11	10	—	—	4	3	—	—
Central and Southern Asia with Formosa.	38	10	28	7	18	10	2	—	14	13	1	3
Northern Siberia . .	—	3	—	—	—	2	4	—	5	1	—	—
Indian Ocean . . .	6	4	—	1	—	4	—	—	1	3	—	—
Japan	22	3	26	9	22	6	6	5	3	35	3	4
East Indies and Polynesia	21	14	6	4	20	4	34	13	7	41	37	32
Australia and New Zealand	5	3	1	1	—	—	1	1	2	4	18	23
Kurile Islands . .	16	6	15	7	5	4	3	1	4	16	2	4
Aleutian Islands and Alaska	18	10	14	—	7	—	2	10	—	13	1	—
North America . .	4	3	3	1	3	—	—	3	—	1	—	—
Central America . .	36	8	6	3	3	1	15	1	3	6	1	—
South America . .	13	4	8	3	1	—	1	18	3	3	—	—
North Atlantic (with Baffin Bay and North Sea)	21	10	13	4	2	3	3	—	—	1	—	—
South Atlantic . .	1	2	4	—	1	1	—	—	2	2	—	—
Africa	1	—	—	2	—	—	—	—	1	—	—	—
Total	219	101	134	78	93	45	71	52	49	142	63	66

Although the data do not refer to the same period of years, there are some very striking similarities and contrasts between the figures for the different observatories. We find that at Kew, Uccle, Sverdlovsk, and Pasadena, the anaseisms predominate, whilst at Zi-Ka-Wei kataseisms are recorded nearly three times as frequently as anaseisms; at Riverview the numbers of occurrences of each of the two types of movements are nearly equal. In Europe and central Asia there are more anaseisms than kataseisms from epicentres in most of the regions except the first which gives movements of both types. The figures for Pasadena bring

out the interesting fact that Central American earthquakes give anaseisms, while shocks in South America and those in Alaska and the Aleutian Islands are kataseismic. At Zi-Ka-Wei kataseismic waves are generally recorded from the epicentres round the northern and western Pacific. From these results it may be inferred that most of the earthquakes in different parts of the world are produced by crustal disturbances which are characteristic of the regions, and which tend to operate in specific directions.

Characteristics of Deep Focus Earthquakes

Seismologists were sceptical when Turner first called attention to the abnormal observations which he interpreted as being from earthquakes with foci at depths of several hundred kilometres. One of their strongest objections to the hypothesis was the belief that at such depths the processes which generate earthquakes could not be effective. The striking confirmation that Turner's hypothesis was correct has been followed by much speculation as to the means by which deep focus earthquakes are caused.

The early belief that these earthquakes are caused by deep-seated explosions, or by the caving in of portions of the earth's crust surrounding cavities, had to be abandoned when it was discovered that the type of initial movements for deep focus earthquakes is not the same in all directions from the epicentre. It is obvious that the movements from an explosion would be anaseismic in all azimuths, and that those from a collapse of rock would be kataseismic. The distributions which are observed with anaseisms in some regions and kataseisms in others indicated that shearing movements must occur. The original disturbance may consist of shearing alone, or may possibly be a combination of shear and explosion or of shear and collapse, but it cannot be due to processes which do not give rise to shear, directly or indirectly.

Gutenberg and Richter have classified the types of onsets

recorded at Pasadena from deep focus earthquakes according to the locality of the epicentres. They find that the results are in remarkable agreement with those for normal shocks. The initial movements from the deep focus earthquakes in particular regions are nearly always of the same type, and the geographical distribution of the shocks producing anaseisms and kataseisms at Pasadena is similar to that for normal shocks.

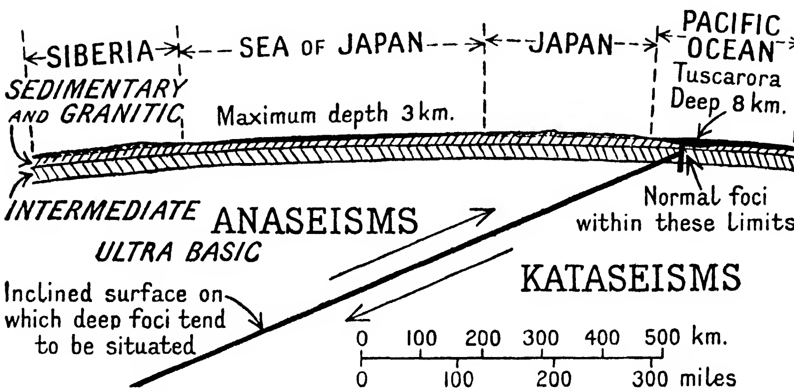


Fig. 68.—Distribution of foci along an east–west section near Japan from Siberia to the Pacific

It will be recalled that in the regions around Japan the deep focus earthquakes are systematically arranged in two belts (Figs. 60 and 61). Honda examined the distributions of the anaseismic and kataseismic movements from the 45 deep focus earthquakes included in his map. He found that, for nearly all the earthquakes beneath the region where the principal belt crosses Japan, the movements were kataseismic to the north-east and anaseismic to the south-west of the belt. Fig. 68 illustrates the variation of the depth of focus over a section crossing the Sea of Japan in the region where the contour lines of Wadati's map are most widely spaced. Apparently the foci tend to occur along an inclined surface which slopes downwards beneath Japan from the region of the Tuscarora Deep. For most

of the earthquakes the rocks above this inclined surface are moved up the slope relative to the deeper rocks ; these movements are represented by the arrows of the sectional drawing. Around other parts of the Pacific the deep focus earthquakes originate beneath regions on the continental side of the belt where normal focal depths predominate, and in these localities there are indications of inclined planes of weakness which correspond with that beneath Japan. Thus it appears likely that huge " faults ", extending to a depth of about 400 km. or more, can exist in the earth's crust and that deep foci are on such faults. Volcanoes, live and extinct, are found above the line where the fault is at a depth of 100 km., while ordinary earthquakes with shallow focus occur near where the fault approaches the surface.

Chapter XIII

MECHANISM OF EARTHQUAKES

It has been shown in the preceding chapters that throughout the world seismic activity is most marked along the steeper flexures in the earth's crust, in localities where there is evidence of secular movement, and in mountains which are geologically new and where we have no reason for supposing that a state of equilibrium has been reached by the rocks. The fact that earthquakes occur in these regions was responsible for the theory that they are due to the sudden dislocations of the crust when there are spasmodic movements between adjacent masses of rock. The observations of anaseisms and katasecisms, both for the normal and for the deep focus earthquakes, have demonstrated that the successive movements in any region tend to be in the same direction.

There is good reason to believe that the cause of earthquakes is to be found in the processes which lead to the formation of mountains. Unfortunately, at present, although various theories have been propounded, we do not know how the mountains are built.up, and it follows that we cannot explain the origin of earthquakes. Many observations have been made which are related to the formation of mountains and the effects of their weight upon the earth's crust. Among the most important of the theories are those of continental drift and of isostasy.

The theory of continental drift was suggested tentatively by A. Snider in 1858 and was developed by A. Wegener in 1915. Wegener believed that the remarkable similarity between the configuration of the coastlines of South America and of Africa is due to these land masses having,

at some early stages in the earth's history, formed part of a single continental unit. He called attention to corresponding similarities between other coastlines, including those of Greenland and Norway, Greenland and Labrador, Africa and Arabia, and of New Guinea and Australia. To explain these similarities he suggested that the land masses of the globe were all originally part of a single great continent surrounding the south pole, and that this continent had broken up into pieces which had separated by a gradual drifting over the underlying rocks. The drifting was towards the equator and to the west. In support of the theory Wegener called attention to many remarkable similarities between the biological and geological characteristics of regions which are now widely separated ; these resemblances could be explained if the regions had once been joined. It was also suggested that the great mountain chains and island arcs might have been formed by crumpling at the front of the drifting land masses.

Observations in different parts of the world have shown that the intensity of gravity, corrected to mean sea level, is unduly low in mountainous regions and high in oceanic regions. Hence the average density of the rocks in the earth's crust is low where there is the extra weight of the mountains to be supported, and high where the loading is diminished. It has been found that these two effects are roughly equal, the extra load of the mountains being offset by the deficit in the average density of the rocks beneath them. This balance between the weight of the outer part of the crust and the density of the subjacent material is known as "isostasy". W. Heiskanen has suggested that beneath the mountains there is a depression of the discontinuity between the superficial rocks in the crust and the deeper heavier rocks; similarly it is supposed that the denser rocks bulge upwards beneath the oceans. According to the theory of isostasy the total mass of the rocks would be the same for columns of equal sectional area at A, B, and C in Fig. 69.

The different parts of the earth's crust are continually

subjected to forces which disturb its equilibrium. The cooling of the earth sets up stresses in the crust; the weight may be lessened by erosion or increased by the accumulation

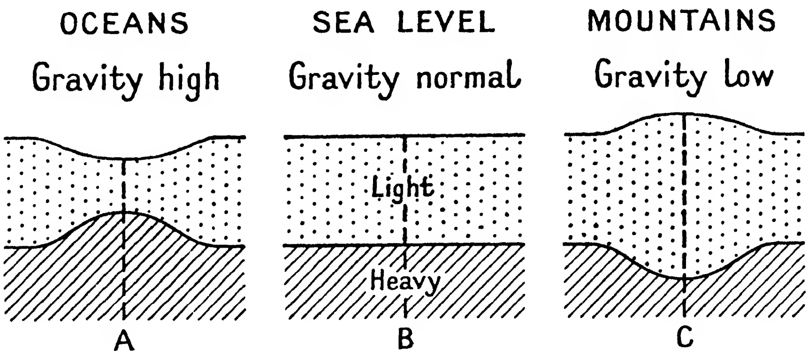


FIG. 69.—Isostasy and anomalies of gravity

of sediments; chemical changes produce local alterations of volume, and there is heating from radioactive materials.

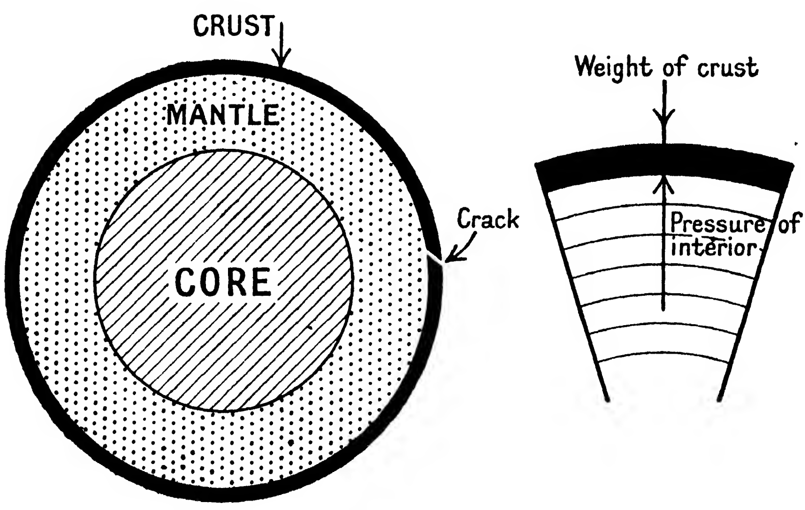


FIG. 70.—Cracking and overlapping of crust due to cooling

The stresses which are produced in the crust cause it to buckle up, and if the buckling is carried far enough the rocks are fractured. Again, if it is supposed that at one stage the

weight of the crust is entirely supported by the pressure of the underlying body, then as the body cools without immediate shrinkage there is less support from below for the crust (Fig. 70). The crust is strong enough to stand this strain for a while, but eventually it will crack somewhere. The two sides of the crack tend to overlap. The volume inside the crust is reduced and the weight is again borne by the underlying body.

Crustal Blocks and their Movements

By processes such as those mentioned above the crust is cracked and broken in many regions, so that it resembles a mosaic in which the interlocking pieces are huge blocks or structural units. The boundaries between adjacent blocks are sometimes visible as faults near the surface, but generally they can only be traced from a special survey ; the area of the units may be hundreds of square miles. In the regions where the deep focus earthquakes occur it appears that some fractures are continued far beneath the crust.

From changes which had been observed in the levels of different regions around the epicentre of the Tango earthquake of 7th March, 1927, C. Tsuboi inferred that each of the crustal blocks behaves as a rigid body, and that the blocks may be tilted slightly in different directions. The forces acting on the blocks are continually changing on account of shrinkage and the variations in loading due to erosion, deposition of sediments, rainfall and other agencies. Movements between the blocks are not easily produced owing to friction at the faces and irregularities along the fractures. When the balance of the forces is disturbed stresses are set up in the rocks beneath large areas, and there is a gradual accumulation of energy. The stresses increase and eventually one or more of the blocks moves with a jump. The dislocation occurs where the forces preventing motion of the blocks are weakest, and may be at a considerable distance from the region where the stresses are first

set up. Fig. 71, is an example of the way in which the movements may be generated. If the rocks on either side of a fault are locked together and subjected to forces in opposite directions, the strain in the neighbourhood of the lock is partly compression, partly expansion. When the locking piece breaks there is a relief of the strain, slipping occurs at the fault and the blocks are tilted slightly. The tilting is very small, and the movement along the fault cannot be observed at the surface except for very great earthquakes. When the dislocation occurs the potential energy stored up in the rocks is converted into kinetic energy setting up wave motion in the earth.

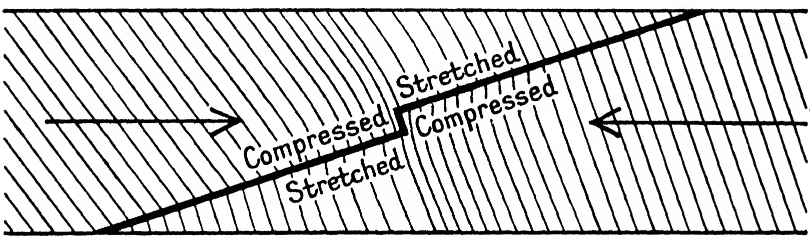


FIG. 71.—Strains with opposing forces applied to interlocking blocks

The occurrence of aftershocks indicates that the strain over the whole region may not be released at the time of the original dislocation. The sudden disturbance at the focus upsets the equilibrium in the surroundings, and other shocks occur at intervals until the whole region has settled down to a stable condition. Centuries may then pass before the stresses become sufficient to produce another earthquake.

The initial dislocation need only occur along a small part of the fault, for the release of the strain in any region increases that in the surroundings, and they too may be set in motion. Accordingly the dislocations along a great fault may commence as a localized slipping of the rocks on one side relative to those on the other, and proceed practically instantaneously along the whole length of the fault. It has been maintained that the movements of the San

Francisco earthquake originated in the part of the San Andreas Fault nearer to the city, and that the displacements were less for the more remote parts of the fault. For this earthquake, and for many others which have also been accompanied by visible displacements along great faults, the seismic intensity was greatest in a narrow belt centring along the fault and diminished on either side.

The stresses which cause earthquakes are built up so insidiously that, even now, they may be nearing the limit of safety in regions where great earthquakes have been unknown throughout historic times. The fact that there is no record of a great earthquake having occurred in Britain and North-western Europe shows that a catastrophe of this sort is unlikely, but does not prove that these regions are immune. In this connexion we may recall that a severe earthquake occurred on 20th November, 1933, in Baffin Bay ; this earthquake aroused considerable interest as there is no record of any large shock having previously been experienced in this locality.

Hypothetical Secondary Causes of Earthquakes

Although it is now generally conceded that the primary causes of earthquakes are volcanic activity and dislocations of the earth's crust, we find in some works a great reluctance to abandon old theories that they are in some way connected with outside agencies like the attraction of the heavenly bodies or meteorological conditions. To explain the importance of these factors, which could only produce very small disturbances in the crust, it has been suggested that if the rocks are already strained nearly to their elastic limit the additional stress, like the proverbial last straw, may be just sufficient to precipitate a fracture. Hence the operation of these factors has been brought forward as a " trigger " effect or secondary cause of earthquakes.

If the occurrence of earthquakes were affected by the attraction of the sun and moon, earthquakes would be more

numerous when the stresses are greatest. The periods of the maximum stress or greatest pull will occur when the sun and moon are nearest to our planet—that is in perigee and perihelion, and again when they are acting in conjunction or at the syzygies. It has occasionally been claimed that earthquakes are *slightly* more numerous at these particular periods than at others, but the excesses found are so small that they may be due to chance in the selection of the data examined. In a similar way the comparisons which have been made between the occurrence of earthquakes and the state of the tides have led to very inconclusive results ; in fact it has been shown by C. G. Knott that, for Japan at least, there is no connexion between the phases of the tide and the frequency of earthquake disturbances. Among the meteorological factors which have been considered are the variations in the atmospheric pressure, fluctuations in temperature, and the incidence of wind and rain, but again there is little, if any, evidence to show that they are connected with earthquakes.

These hypotheses have been discussed in many writings since the earlier editions of this book were published. The most recent work in this connexion is the paper, referred to on page 157, in which Jeffreys has demonstrated the fallacy of the claims that earthquakes are affected by influences which vary with the season of the year or with the time of day. There is, therefore, no reason to modify the conclusion reached by Milne in the sixth edition (*Earthquakes*, p. 377), that :

> Speaking generally, so far as I know, neither tidal, barometric, thermometric, solar, lunar or other epigene influences beyond those mentioned show a relationship to the periodicity or frequency of megaseismic activity. Their frequency is apparently governed by activities of hypogene origin.

Prediction of Earthquakes

Ever since seismology has been studied, one of the chief aims of its students has been to discover some means which

would enable them to foretell the coming of an earthquake. At the outset it must be emphasized that any prediction of an earthquake, to be of value, must give the region in which it will occur as well as the time ; also that, with many earthquakes occurring daily somewhere or other in the world, the operation of the ordinary laws of chance may lead to occasional successes in so-called forecasts based upon unsound methods. It is recorded in history that predictions depending on various observed phenomena, such as changes in the waters of wells or springs, the occurrence of underground rumblings, or the attractions of the sun and moon, etc., have sometimes been successful. Rather than accredit the ancients, or those of more modern times, who, in consequence of their feelings or observations, have foretold the coming of an earthquake, with a knowledge of premonitory signs, we might regard the records of these prognostications as the survival of accidental guesses. We conclude that a few successful warnings have been remembered whilst countless failures have been forgotten. The unexpected or inexplicable is always more likely to be noticed and remembered than the ordinary. For example, now that it is generally realized that weather forecasting is based upon scientific observations and inferences, publicity is given to the rare occasions on which the forecasts are inaccurate, and the successes are accepted without comment.

The most rational suggestions which have been made for prediction of earthquakes are based upon the observations of phenomena of hypogene origin. Before the Mino-Owari there was a marked increase in the number of preliminary shocks along the line of the valley where the great disturbance originated. It has been suggested that the small foreshocks indicated the removal of obstacles on a fault plane and that the occurrence of such a series of little shocks might be taken as a warning of other impending disasters. Another suggestion is that before a great earthquake the region in which it occurs changes in level. Changes in the relative positions of various points, both in azimuth and in level,

have been found as a result of repeated surveys in Japan and in America, but no close connexion has been established between the magnitude of the changes and the occurrence of earthquakes. Again, it has been suggested that the increase in the strain around the epicentre before an earthquake might be indicated by changes in the velocity with which seismic waves are propagated. All these suggestions, however, are of academical rather than practical interest, and the possibility of evolving a sound method of earthquake prediction is very remote.

CHAPTER XIV

MICROSEISMIC DISTURBANCES

MORE than a century ago, before there were any sensitive seismographs, a high standard of precision had been attained in scientific measurements, and it was discovered that in certain delicate experiments the instruments were disturbed by vibrations of the ground. One of the first examples was the discovery by Kater, early in the nineteenth century, that determinations of gravity from pendulum observations in London were affected by these vibrations. Mention may also be made of a series of observations carried out during the years 1880–82, by G. and H. Darwin in the Cavendish Laboratory at Cambridge.[1] The main object in these experiments was to determine the disturbing influence of gravity produced by lunar attraction. The result which was obtained showed that the soil at Cambridge was in such an incessant state of vibration that whatever pull the moon may have exerted upon the instrument which was employed was masked by the effects of the earth movements, and the experiments had to be abandoned. The existence of these oscillations of the ground has since been established from the records of seismographs, and much information has been obtained regarding the nature and causes of the disturbances. In German there is the very appropriate name of *Bodenunruhe* for these movements ; we have no exact English equivalent of this other than the literal translation "ground unrest", and the terms "microseisms" and "microseismic disturbances" have been adopted.

At some observatories movements caused by agencies in the immediate neighbourhood are recorded in the seismo-

[1] *Reports of the British Association :* 1881, p. 91 ; 1882, p. 95.

grams. Rapid vibrations are frequently caused by traffic or machinery, and strong winds striking a high building or trees in the vicinity may set up irregular oscillations of the ground with a period of about twenty seconds. The most important of the movements, however, are those with periods from about three to ten seconds which cannot be ascribed to local causes ; these oscillations are to a greater or lesser extent nearly always shown in the seismograms. Throughout this chapter the terms microseisms and microseismic disturbances are used in a restricted sense, applying only to these movements which are sometimes known as "ordinary" microseisms. Portions of seismograms, illustrating large microseisms recorded at three observatories equipped with seismographs of different types, are shown in Fig. 72. Smaller microseisms are shown in the deep focus earthquake records of Fig. 45. From the records we see that the movements occur in each of the three components. The period of the oscillations remains fairly constant for hours at a stretch, but the amplitudes increase and decrease rhythmically in a manner which suggests that more than one train of waves are affecting the seismograph.

A scheme of tabulation had to be devised before the changes in the microseisms from time to time or from place to place could be examined. The period and amplitude of the oscillations are the characteristics usually measured in studying wave motion, but the microseismic amplitudes do not remain constant and need special treatment. In the scheme adopted the tabulations are made for certain hours, and the measurements refer to the most prominent group of microseisms during an interval (usually of 30 minutes), centred at the hour. The actual amplitude of the ground movements are obtained by dividing the recorded amplitude by a factor which depends upon the constants of the seismograph ; the unit used in dealing with these small ground movements is the thousandth part of a millimetre, known as a micron and written as 1μ. The hours selected for the tabulations are generally 0 h, 6 h.,

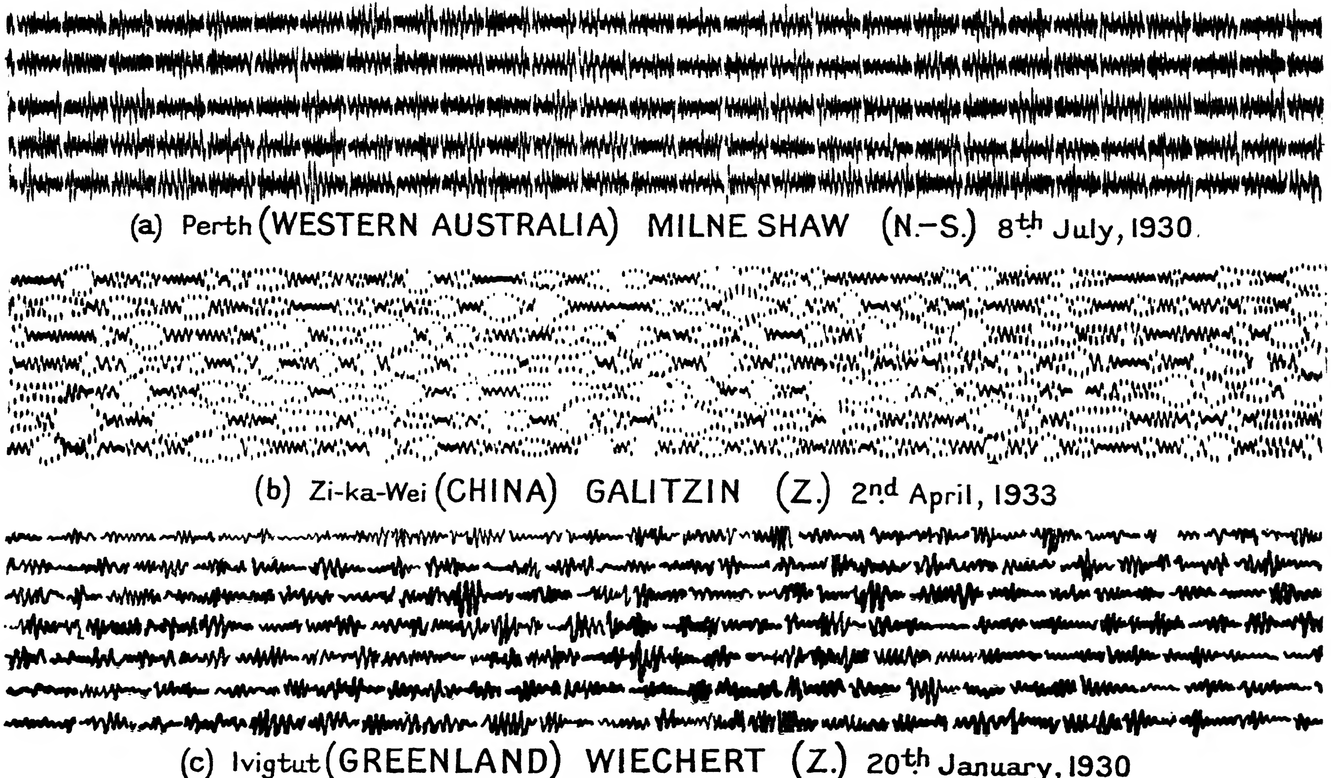


FIG. 72.—Records of microseisms

12 h. and 18 h., G.M.T. The measurements of the microseisms at a number of observatories have been published and a large amount of statistics is available.

There is a well-marked seasonal variation in the microseismic activity, the larger amplitudes and the longer periods occurring in the winter; in summer the period is generally about 3 to 5 seconds and the oscillations are so small that they are scarcely perceptible in the seismograms. The seasonal change is brought out clearly from the mean values of the amplitude and period for each month, especially if the values for a number of years can be combined to smooth out any abnormal values. The monthly means for the microseisms at Eskdalemuir, Kew and De Bilt are set out in the table given on page 195.

The tabulated values show how the amplitude decreases progressively and the period gets shorter during the first half of the year, and how the changes are reversed during the latter half. The mean periods are about the same for the three observatories but the amplitudes behave in a very peculiar fashion; at Kew the horizontal and vertical components are nearly equal, whilst at De Bilt the horizontal movements are very much the larger. An explanation of this difference between the microseisms at these observatories is given later.

The changes in size of the microseisms at seven observatories in Great Britain throughout the month of January, 1930, are depicted in Fig. 73. The size of the microseisms recorded at any time varies from place to place, but we see that when there is a pronounced change in the amplitude at one observatory there are corresponding changes at the others, indicating that the movements extend over the whole of Britain. Observations from the continent show that the disturbances are related over a much wider region, and that strong microseisms are recorded simultaneously at observatories in all parts of northern Europe and western Siberia. The microseisms in North America also occur simultaneously over the greater part of that continent.

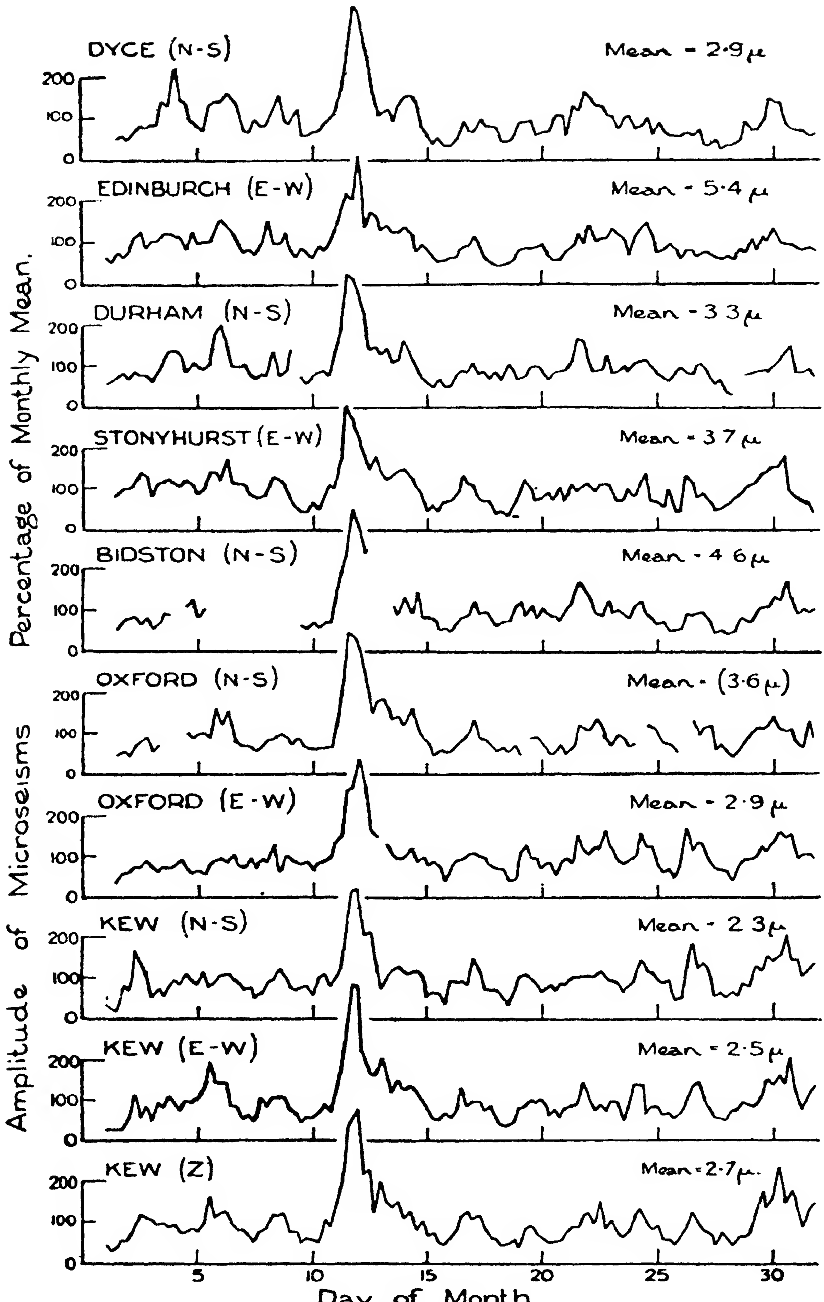


FIG. 73.—Amplitudes of microseisms in Britain, January, 1930

MONTHLY MEANS OF AMPLITUDE AND PERIOD OF THE MICROSEISMS RECORDED AT ESKDALEMUIR, KEW AND DE BILT

Station	Component	Years	Month: Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean for year
			Mean amplitude in microns												
Eskdalemuir .	N.–S.	1911–24	2·5	2·3	1·8	1·2	0·7	0·5	0·3	0·5	0·9	1·2	1·8	2·3	1·3
Kew . . .	N.–S.	1926–34	2·3	1·6	1·4	0·9	0·5	0·4	0·3	0·5	0·6	1·1	1·6	2·0	1·1
,, . . .	Z.	1935–7	2·4	2·3	1·1	0·8	0·4	0·3	0·3	0·2	0·7	1·3	1·4	1·8	1·1
De Bilt . .	N.–S.	1923–9	5·0	4·5	3·0	2·5	1·5	1·5	1·1	1·5	2·1	2·9	3·9	4·9	2·9
,, . .	E.–W.	,,	6·1	5·6	3·6	3·1	1·8	1·9	1·3	1·9	2·5	3·8	4·9	6·0	3·5
,, . .	Z.	,,	2·4	2·2	1·3	1·1	0·8	0·9	0·7	0·8	1·1	1·4	1·9	2·4	1·4
			Mean period in seconds												
Eskdalemuir .	N.–S.	1911–24	6·1	6·0	5·7	5·3	4·7	4·6	4·3	4·5	5·0	5·2	5·6	5·9	5·2
Kew . . .	N.–S.	1926–34	6·5	6·1	5·9	5·4	4·9	4·7	4·4	4·6	5·0	5·4	6·0	6·4	5·5
,, . . .	Z.	1935–7	6·4	6·2	5·7	5·6	5·1	4·8	4·7	4·8	5·3	6·1	6·3	6·2	5·6
De Bilt . .	N.–S.	1923–9	6·5	6·4	5·9	5·6	5·0	5·0	4·6	4·9	5·2	5·5	5·9	6·2	5·6
,, . .	E.–W.	,,	6·4	6·3	5·8	5·5	4·8	4·8	4·5	4·7	5·1	5·4	5·8	6·1	5·4
,, . .	Z.	,,	6·4	6·2	5·5	4·9	4·1	4·0	3·6	3·9	4·4	4·8	5·3	5·8	4·9

Thus the oscillations are propagated over thousands of square miles, and a very great amount of energy must be available somewhere to generate them. The most obvious sources from which this energy might be obtained are atmospheric storms.

The general similarity between the characteristics of the microseisms and those of sea waves, and especially the close agreement between the periods, led to the belief that the phenomena are related, and the hypotheses which have been propounded to explain the origin of microseisms have mostly endeavoured to show how they could be generated from the waves caused by depressions over adjacent seas. The hypotheses of E. Wiechert, E. Gherzi and S. K. Banerji are the best known. Wiechert attributed the microseisms to the impact of waves against the coasts, and his hypothesis has been developed by Gutenberg and other German seismologists. Gutenberg claims that the large microseisms recorded in Europe are mainly caused by the beating of waves along the precipitous western coast of Norway. According to this hypothesis the steep rocky coasts are necessary to ensure that the waves break violently and transfer the energy to the ground with a minimum amount of friction. Gutenberg has considered the order of magnitude of the quantities involved in the process and concludes that the energy transferred to the coast by the breakers is large enough to cause the microseisms. No exact explanation of how the breaking of the sea waves sets the ground in oscillation is given, but presumably each breaker is supposed to act like a tiny earthquake and generate surface waves. The difficulty confronting this suggestion is that the waves do not break simultaneously along the whole coastline and the agreement between the periods of the microseisms and of the sea waves is not explained. Gherzi and Banerji have noted occasions on which the microseisms were large while the storms were so far out over the oceans that the seas near the coasts were undisturbed. The former has also shown that large microseisms are recorded at Zi-Ka-Wei

when there are cyclones in the surrounding regions, but not when the sea waves are due to high monsoon winds. The hypothesis which he put forward, and which has been elaborated by D. Bradford, is that the microseisms are caused by atmospheric oscillations or " pumping " near the centre of a cyclone ; in support of this hypothesis Bradford has called attention to an interesting occasion when large microseisms at St. Louis coincided with well-developed oscillations of pressure at Washington. It is thought that the atmospheric oscillations not only generate microseisms when the storms pass over land, but that they are also effective over the oceans, the oscillations being propagated through the water to the sea bed and there transformed into microseisms. Banerji has shown that with a storm approaching India from the Bay of Bengal the largest microseisms occur several hours before it reaches the coast, and that the microseisms diminish after the storm-centre crosses the coastline. To explain these observations Banerji supposes that the sea waves cause changes of pressure over the sea bed, thus setting up forced oscillations which are propagated as microseisms when they reach the coast. The objections to this hypothesis are that the sea waves are superficial phenomena and the amplitudes fall off so rapidly with the depth that there is practically no disturbance in deep water, and also that the length of the sea waves is very much smaller than that of elastic waves having the same period in the rocks beneath the oceans. In discussing these difficulties F. J. W. Whipple has pointed out that the ocean waves, being produced by the interaction of wind and water, differ from the permanent waves of the mathematical theory, and has suggested that when gravity waves are being formed or modified by the action of wind, waves of compression reach the sea bottom and generate disturbances in the underlying rocks. Each train of waves extends over a few wave lengths and is equivalent to a comparatively small oscillator ; there is no fixed phase relation between any two of these oscillators.

The grouping of the microseismic waves suggests that the phase relations between the trains of waves from different sources persist for periods of the order of half a minute. For a little while the displacements due to the several sources cancel out, and then the oscillations increase again in amplitude.

The Nature of Microseisms

Until a few years ago the study of microseisms was in a very unsatisfactory state. The nature of the movements and the reasons for the variations from place to place were unknown, and the theories were unable to explain how the movements were generated. The difficulties were partly due to inconsistencies among the older tabulations, and it was decided to collect some new data, special precautions being taken to ensure uniformity in the measurements of the ground movements. The amplitudes and periods of the microseisms recorded at the seven seismological observatories in Great Britain were first examined for the month of January, 1930. The tentative conclusions drawn from these data were that—

(i) the microseisms are Rayleigh waves propagated through the outer layers of the earth's crust,
(ii) the absolute amplitude of the ground movements varies over a wide range depending on the locality and geological structure, being larger where the sedimentary rocks are of greater thickness,
(iii) the fluctuations in the amplitude in any region are closely related to those in the other regions.

These conclusions had to be verified from observations of microseisms in other regions and tabulations for the month of January, 1930, were collected from about 60 observatories in all parts of the world.

The first question to be considered was whether the

results obtained from seismographs of different types are strictly comparable. The seismographs recording photographically, and these are the types used at the observatories in Britain, give consistent values. With mechanical registration the friction between the stylus and the smoked sheet has to be neglected in the calculation of the ground movement corresponding with a given displacement on the record, and the amplitudes tend to be underestimated. The uncertainties due to friction add considerably to the difficulties of determining the genuine differences between the amplitudes in different regions. It has also been found that at some stations with seismographs recording mechanically the amplitudes of the microseisms are systematically larger by day than in the night, whilst those obtained with photographic recording do not show any regular variations throughout the 24 hours. Dr. Whipple has suggested that with mechanical registration the friction of the stylus may change regularly, being overcome during the day when there are very rapid oscillations due to traffic, etc. The diurnal variations would be greatest at observatories subject to these influences; examples supporting this suggestion are found at Copenhagen where with little disturbance near the seismographs there are no diurnal variations, and at Hamburg where traffic passes near the observatory and the variations are large.

The theory that the movements are Rayleigh waves in the granitic and sedimentary layers of the crust, and that the amplitudes of the microseisms are affected by the thickness and composition of the sedimentary material, received striking confirmation. The mean amplitudes for the month, obtained from observatories in Europe recording the horizontal and vertical components with Galitzin seismographs, together with the ratios of horizontal to vertical amplitudes, are set out in the following table.

Observatory	Mean amplitude (microns)			Ratio	
	A_N	A_E	A_Z	A_N/A_Z	A_E/A_Z
Kew	2·3	2·5	2·7	0·9	0·9
De Bilt	5·9	7·5	2·9	2·0	2·6
Strasbourg	5·8	3·6	1·9	3·1	1·9
Abisko	1·1	1·0	1·5	0·7	0·7
Copenhagen	1·4	—	1·3	1·1	—
Pulkovo	0·8	0·9	1·1	0·7	0·8
Kučino	0·9	0·9	1·0	0·9	0·9

At Abisko and Pulkovo the ratio of the horizontal to vertical components (0·7) is about the value for Rayleigh waves in a homogeneous medium with Poisson's ratio 0·25. These observatories are situated on the Archæan rocks which are nearest to the sub-continental granitic layer, and for which roughly speaking the elastic constants of granite are appropriate. For Kew, Copenhagen and Kučino, where the formations may be termed "consolidated", the horizontal and vertical amplitudes are approximately equal. This would be expected from the theory of Rayleigh waves in stratified media if the properties of the sedimentary rocks are appreciably different from those of the granite. At De Bilt and Strasbourg on recent "weak" formations the differences between the properties of the superficial layers and those of the granite are larger, and the horizontal amplitudes are two or three times the vertical amplitudes, again agreeing with the theory. The classification of observatories as being situated on rock, consolidated, or weak formations refers to the general features of the surroundings. It is not worth trying to discriminate further between the formations owing to the numerous changes in the structure of the earth's crust and irregularities in the stratification. Probably changes of structure are not serious unless the areas of the formations are large compared with the wave length of the microseisms, which is from about 10 to 30 km.,

or unless the thickness of the superficial material exceeds 0·1 km.

A further test was made by examining the ratios of the horizontal to vertical movements from the individual observations at De Bilt, Kew and Abisko, the microseisms at these observatories being taken as examples for weak formations, for consolidated formations, and for rock respectively. To eliminate the effects of errors of measurement, etc., the ratios were collected into groups according to the period of the microseisms. It was found that at De Bilt the ratio of the horizontal to vertical amplitudes decreases as the period lengthens, being about 3 : 1 for microseisms of period 5 sec. and 2 : 1 for those of period 9 sec. At Kew the variation in the ratio is smaller, the values decreasing from about 1 : 1 for period 5 sec. to 0·8 : 1 for period 9 sec. The ratio, 0·7, at Abisko does not vary with the period. The variations in the ratios at De Bilt and Kew were later confirmed from more extended series of observations. For each of these observatories the results accord with the theory that the microseisms are Rayleigh waves in the granitic and sedimentary layers. No variation of the ratio with the period would be expected on rock, but on the other formations the effect of the superficial material would be greater for the microseisms with the shorter periods since their wave length is less; the observations that the effect is greater for weak than for consolidated strata also conform with the theory.

At Strasbourg the amplitudes of the N.–S. component are, on the average, about half as large again as those of the E.–W. component. Other investigators had previously noticed this remarkable difference but could find no reason for the anomaly. It can be explained from the theory of Rayleigh waves propagated through rock covered by a layer of sedimentary material. The formulæ used in the theory depend upon the assumption that the horizontal extent of the material is very large compared with the wave length of the microseisms. This assumption does not hold for

Strasbourg, situated in the valley of the Rhine which runs from S.S.W. to N.N.E. with mountains on either side. The weakest alluvial deposits are along the valley, the longitu-

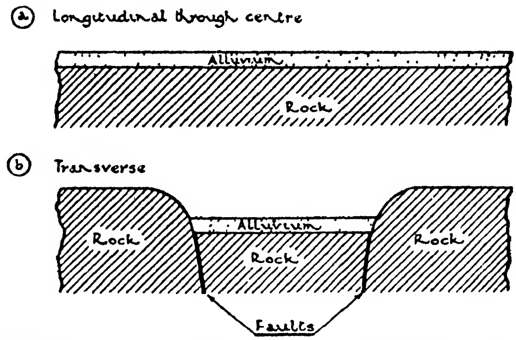


FIG. 74.—Sections of rift valley. (*a*) Longitudinal through centre. (*b*) Transverse

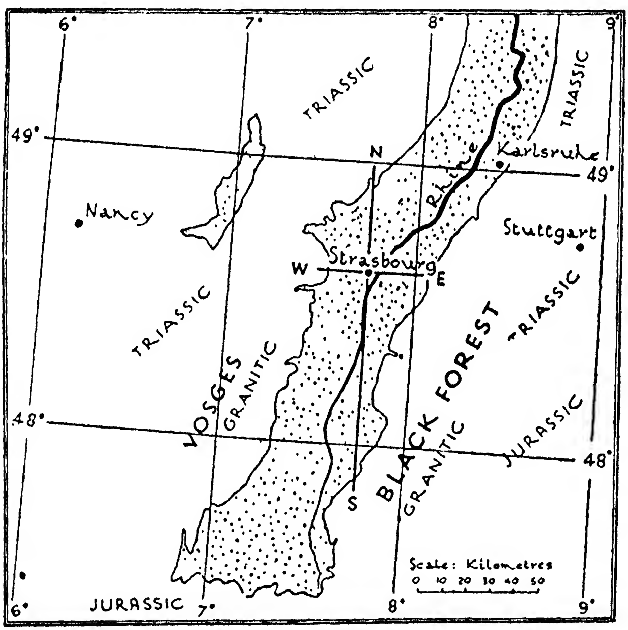


FIG. 75.—Distribution of strata around Strasbourg

dinal and transverse sections being roughly represented in Fig. 74. A geological map of the surrounding country appears in Fig. 75; the map shows how the weak upper

strata of alluvial deposits along the valley extend further to north and to the south than to the east or west, affecting the amplitudes of the N.–S. component more than those of the E.–W. component. The wave length of the microseisms is comparable with the extent of the weaker formations, so the theory of Rayleigh waves in materials of infinite horizontal extent does not apply as closely as for observatories where the surrounding strata are more uniform.

J. Lacoste has compared the microseisms at Strasbourg with those at Saverne, near the edge of the valley some 35 km. to the W.N.W., and at Ste-Marie-aux-Mines, located in the mountains about 60 km. S.W. of Strasbourg. The mean amplitudes for the N.–S. components at the three stations are in the proportion,

Strasbourg : Saverne : Ste-Marie = 2·5 : 1·4 : 1·0.

Thus the amplitudes near the boundary between the alluvium and the rock are greater than those on rock and less than those where the alluvium is thickest ; this is in accordance with the theory.

Before the geographical distribution of the microseisms can be determined it is necessary to eliminate the effects of the local geological conditions. The amplitudes must be reduced to some uniform standard just as in meteorology atmospheric pressures are corrected to the pressures at mean sea level. The standard chosen for the microseisms is that of Rayleigh waves in the underlying granite. The "standard amplitudes" for any observatory are equal to the amplitudes of the actual ground movements divided, when necessary, by a factor which represents the magnification due to the sedimentary material. The factors by which the amplitudes have to be divided depend upon the ratio of the horizontal to vertical amplitudes, A_H/A_Z. On rock, where $A_H/A_Z = 0{\cdot}7$, the microseismic amplitudes refer to the granite standard and need no reduction. For observatories on consolidated formations the ratio A_H/A_Z is

about unity, and the horizontal amplitudes are from 20 to 100 per cent greater than they would be if the upper layers were replaced by rock ; on weak formations the horizontal amplitudes may be 4 or 5 times the standard values. The vertical amplitudes are affected to a lesser extent by the underlying material. It is possible by the use of standard amplitudes to prepare maps showing the geographical distribution of the microseisms on particular days. The examples of these maps shown in Fig. 76 are discussed later.

Microseisms and Weather

The data collected for January, 1930, provided ample material for study of the connexion between the microseisms in Europe and meteorological conditions. Curves, representing the day to day variations in the averages of the barometric pressure, wind speed and sea disturbance for coastal regions in the British Isles and for various localities of northern and western Europe, were compared with those showing the variations in the microseisms. The comparisons failed to reveal any direct connexion between the microseisms and the pressure, wind or state of sea in the regions considered. The most conspicuous features of the amplitude curves for western Europe (see Fig. 72), are the maxima of the 11th to 12th, when the values were three or four times as great as the means for the month. At this time the average pressure for all the regions considered was the lowest during the month, but on other days the variations in amplitude do not resemble those in the average pressure. On the 11th and 12th the wind and sea disturbance round Britain were large following a sharp rise on the 10th, but the changes around the Norwegian coast were smaller. The absence at this time of any prominent maximum in the sea disturbance off Norway is notable, for this is the locality believed by Gutenberg to be the most favourable for the generation of microseisms.

The observations showed that when the microseisms in

Europe were large, stormy conditions prevailed over the eastern half of the North Atlantic. This is evidence that the microseisms are associated with the storms but does not help to explain the processes involved in generating them. A much more valuable result came to light in the comparisons, however, for it was discovered that the converse is not true, and that stormy conditions over the eastern North Atlantic are not invariably accompanied by large microseisms. This result is of importance since it proves that some other factor beside the "storminess" is necessary for microseisms to be generated. The best example is found in a comparison of the conditions on 3rd January, at 7 h and 11th, January at 18 h. The synoptic weather charts and the microseismic distributions for these two occasions are shown in Fig. 76. In the weather maps the distributions of barometric pressure are shown by the isobars which are drawn for intervals of 10 millibars. The observations of wind are represented by the arrows, and those of sea disturbance by the figures adjoining the coastal stations. For each station the arrow follows the direction of wind, and the force on the Beaufort scale [1] is indicated by the number of barbs; the sea disturbance figures are estimated in accordance with a recognized numerical scale which ranges from calm (0) to mountainous sea (9). The weather maps for the two occasions are very similar, each showing a deep depression between Scotland and Iceland and a secondary off northern Norway, with strong winds and rough seas round north-west Europe. There is a striking contrast between the distributions of the microseisms, the standard horizontal amplitudes on the earlier occasion being much less than half those on the later. The actual horizontal and vertical amplitudes of the microseisms on the two occasions are given in the table on p. 208.

[1] See *Weather*, Abercromby and Goldie, page 14.

SYNOPTIC CHARTS AND DISTRIBUTIONS OF PRESSURE, WIND AND SEA DISTURBANCE.

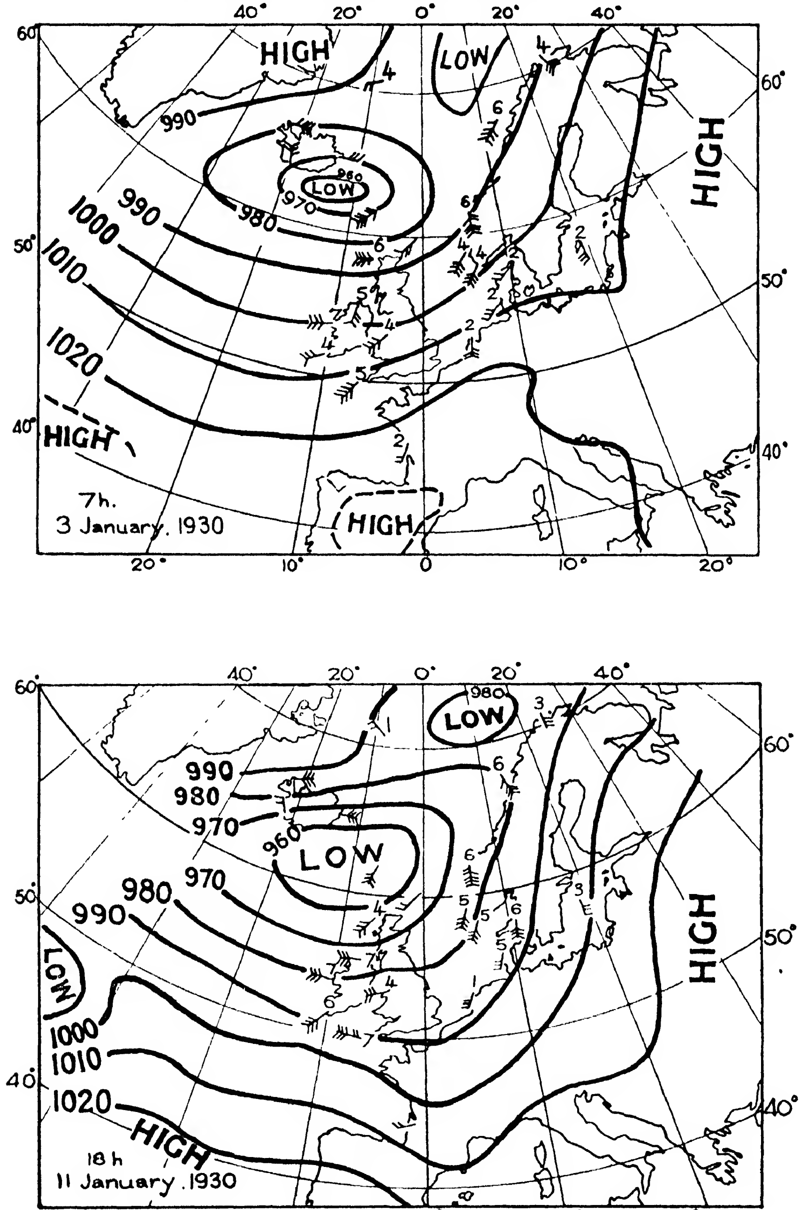
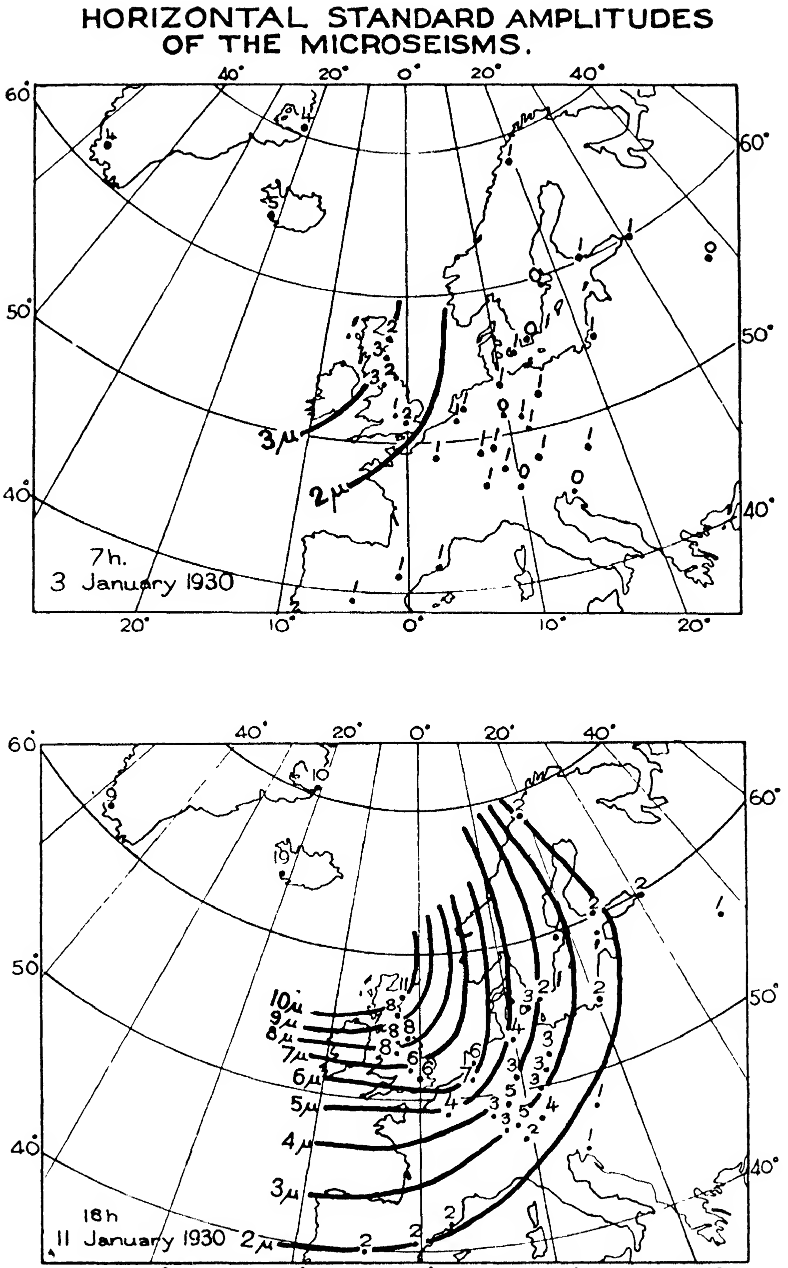


FIG. 76.—Meteorological conditions and prevalence



of microseisms 3rd and 11th January, 1930

AMPLITUDES OF MICROSEISMS AT VARIOUS OBSERVATORIES, JANUARY 1930, 3 D., 7 H. AND 11 D. 18 H.

Observatory	January 3 d. 7 h. A_H	January 3 d. 7 h. A_Z	January 11 d. 18 h. A_H	January 11 d. 18 h. A_Z
	μ	μ	μ	μ
Ivigtut	4	6	9	12
Scoresby Sund	4		10	
Reykjavik	8		33	
Dyce	2		11	
Edinburgh	6		14	
Durham	3		11	
Stonyhurst	4		10	
Bidston	3		16	
Oxford	3		11	
Kew	2	2	9	9
De Bilt	5	3	29	12
Uccle	2	1	15	8
Parc Saint Maur	2		8	
Neuchâtel	1	$<\frac{1}{2}$	5	8
Barcelona	1		5	
Ebro	1		4	
Toledo	1		2	
Abisko	1	1	1	2
Uppsala	$<\frac{1}{2}$		1	
Lund	1		3	
Copenhagen	1	1	5	3
Königsberg	2		5	
Hamburg	4	1	13	3
Potsdam	2		5	
Göttingen	$<\frac{1}{2}$	1	3	3
Leipzig	1		3	
Heidelberg	1		7	
Strasbourg	5	1	11	9
Vienna	2		3	
Munich	1		5	
Zurich	1		7	
Chur	$<\frac{1}{2}$		2	
Zagreb	$<\frac{1}{2}$		2	
Helsingfors	$<\frac{1}{2}$		2	
Pulkovo	1	1	2	1
Means and No. of values	2·2 (35)	1·7 (11)	8·1 (35)	6·4 (11)

The tabulation comprises the horizontal amplitude, A_H, at each of 35 observatories, and the vertical amplitude, A_Z, for 11 observatories; when the amplitudes of two horizontal components are available at any observatory the larger value has been selected. The great difference between the sizes of the microseisms on the two occasions is shown in practically all the records. The mean amplitudes at 18 h. on the 11th and at 7 h. on the 3rd are in the ratios 3·7 : 1 and 3·8 : 1 for the horizontal and vertical components respectively. In fact at most European observatories there was no conspicuous disturbance on the 3rd, but the greatest disturbance of the month was recorded on the 11th.

It has recently been pointed out by E. A. Hodgson that similar discrepancies have been noted in investigations of the connexion between the microseisms recorded at Ottawa and depressions over the north-western Atlantic.

A method of determining the direction from which the microseismic waves approach an observatory has been developed from a study of the differences between the phases of the horizontal and vertical components of the microseisms. The successful application of this method provides a verification that the waves are of Rayleigh type in which the earth particles move round ellipses or circles in a vertical plane. In Rayleigh waves the direction of motion at the surface (see Fig. 32) is opposite to that of a point on a wheel rolling along the ground in the direction of propagation. The vertical component differs in phase from the horizontal component by 90°, and for waves arriving from the cardinal points the movements occur in the sequences set out below:

Direction from which Rayleigh waves approach	Sequences of ground movements
North	up, north, down, south
South	up, south, down, north
East	up, east, down, west
West	up, west, down, east

The movements to the north, to the east and upwards, are

regarded as positive, and those in the reverse directions as negative. Hence for waves from the north and from the east the vertical component precedes the horizontal by 90°, whilst for those from south and from west the vertical lags by 90° behind the horizontal. Actually the phase differences between the components of the microseisms are variable, but the values appropriate for the general direction of approach are dominant. This method of determining the direction of approach of the microseisms has been applied for a number of occasions, including that of 11th January, 1930, considered in the preceding paragraph. The results of 50 comparisons, between the phases of the microseisms recorded at Kew from 17 h. 35 m. to 18 h. 24 m. on that day, showed that the vertical component tended to be 90° in advance of the north component and 90° behind the east component. The microseisms were reaching Kew from the north-west, the direction towards the centre of the depression which was the most conspicuous feature of the weather map for that time; this result is consistent with the distribution of the standard amplitudes mapped in Fig. 75. The direction of approach has also been examined for five other occasions when depressions were located over different parts of the eastern Atlantic and western Europe. In two cases with depressions south-west and south of Britain the microseisms were generated over an area which included regions north and south of Kew. The results for the other three occasions were similar to those for 11th January, 1930, movements from the north-west predominating. The region in which the microseisms were produced does not seem to have been affected by the position of the depressions. The directions of arrival are inconsistent with the theories that the oscillations are caused by the action of wind or waves on steep coasts, or by the motion of waves over shallow water.

The results set out in the foregoing paragraphs show that the connexion between the storms and the microseisms cannot be explained from the current hypotheses. Accord-

ing to either of these the deep depression, appropriately situated, would always be effective in producing microseisms, but we know that such is not the case. Some other agency or combination of circumstances must also be involved. Can it be that the oscillations originate in the atmosphere, and are associated with the discontinuities between air currents of different origins ?

CHAPTER XV

SEISMIC METHODS OF GEOPHYSICAL PROSPECTING

GREAT progress has been made during the present century in the application of physical observations at the surface to the study of the composition and extent of the constituents of the earth's crust, and geophysical prospecting is now a well-established branch of applied science. The oldest of these methods for the investigation of subterranean materials depended upon the magnetic characteristics of different rocks, but the measurements of other physical properties have been found to be equally valuable. Among these other properties are the density, as revealed from measurements of the force of gravity, the elasticity, found from the travel of seismic waves, and the electrical conductivity, determined by the distortion produced in an artificial field of force applied to the ground. In this work we are concerned with the methods depending upon seismic observations, and which are claimed to be the most successful for some purposes.

The development of seismic methods of prospecting can be traced back to the experimental investigations by Mallet, Gray and Milne, and others, in which artificial disturbances of the ground were produced by explosions or by the fall of heavy weights. The object of the experiments was chiefly to compare the types of vibrations and their velocities in different kinds of subsoil. The instruments were very crude according to modern standards, but the results showed that the disturbances were analogous with those from natural earthquakes. In the more recent work the

disturbances are always produced by explosions, and instruments of very great sensitivity have been designed for their registration. Wiechert and Galitzin both realized that the study of artificial earthquakes would be of practical value, and the first success in the application of the seismic methods of prospecting was achieved by L. Mintrop one of Wiechert's pupils.

The theory of the propagation of waves from explosions is the same as that given in Chapter VII for the waves from near earthquakes, but with the explosion very near to the surface there are no complications or uncertainties on

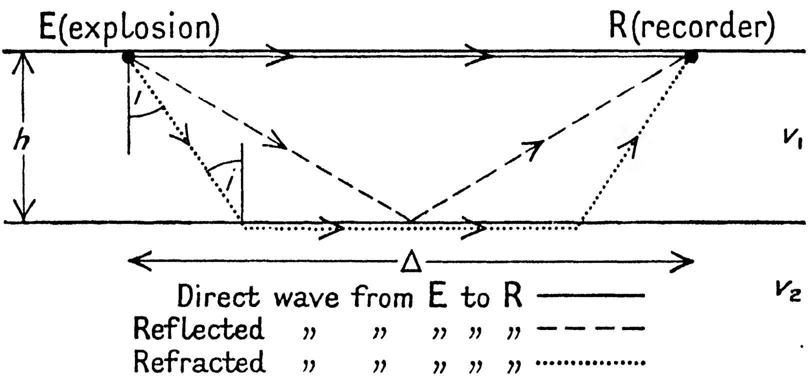


FIG. 77.—Propagation of longitudinal waves from an explosion

account of the focal depth. A further simplication arises from the fact that in prospecting only the longitudinal waves are usually considered.. There are two methods depending upon whether reflected or refracted waves are used.

In the first place we consider the propagation of waves through two media separated by a horizontal discontinuity. If the velocity is greater in the lower medium the direct, reflected, and refracted waves travel from the explosion to the recorder along the paths shown in Fig. 77. We neglect any changes in the properties of the layers with depth, and write v_1, v_2 for the velocities in the upper and lower layers respectively, h for the thickness of the upper layer, and Δ for the distance from the explosion to the recorder.

Assuming that the distance is small enough for the curvature to be neglected, the direct wave travels from the explosion to the recorder in time $\frac{\Delta}{v_1}$, and the travel-time curve is a straight line through the origin. The refracted wave passes twice through the layer at an inclination i, where $\sin i = \frac{v_1}{v_2}$, and the time of travel is $\frac{2h}{v_1 \cos i} + \frac{\Delta - 2h \tan i}{v_2}$; this expression reduces to

$$\frac{1}{v_2}\{\Delta + 2h \cot i\} \quad \text{or} \quad \frac{1}{v_2}\left\{\Delta + 2h\sqrt{\left(\frac{v_2}{v_1}\right)^2 - 1}\right\}$$

Again the travel-time curve is linear but there is a delay of starting $\frac{2h}{v_2} \cot i$. The time taken by the reflected wave in travelling to a distance Δ is $\frac{1}{v_1}\sqrt{4h^2 + \Delta^2}$. In this case the relation between time and distance may be represented by a parabola intersecting the time-axis at $\frac{2h}{v_1}$, when the distance is zero, and approaching the straight line for the travel of the direct wave as the distance increases. The relation between time of travel and distance for each of the three types of waves is shown graphically in Fig. 78.

The reflected wave always arrives after the direct one; the refracted wave follows the direct wave at small distances and precedes it at greater distances when the delay of starting is more than compensated by the higher speed in the lower medium. There is a critical distance, Δ', (Fig. 78*d*) at which the direct and refracted waves arrive simultaneously. At this point

$$\frac{\Delta'}{v_1} = \frac{1}{v_2}\left\{\Delta' + 2h\sqrt{\left(\frac{v_2}{v_1}\right)^2 - 1}\right\}$$

and the formula

$$h = \frac{\Delta'}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}}$$

can be used for the evaluation of h if Δ', v_2, v_1, are known. Alternatively h may be calculated from Δ' and i, the inclination of the refracted wave in passing through the upper

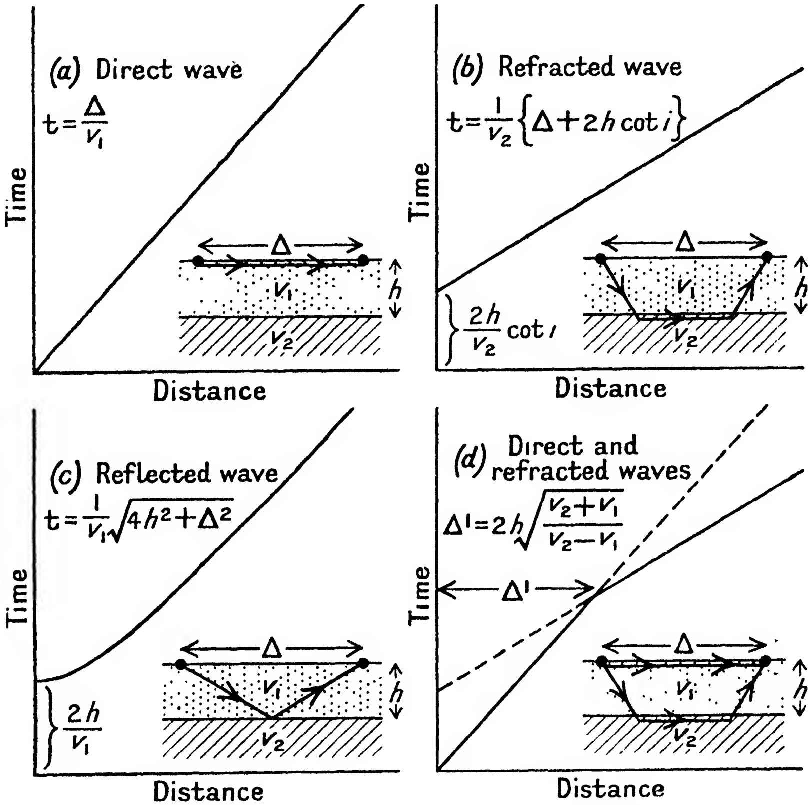


FIG. 78.—Relations between time of travel and distance for waves of different types

layer. The formula is obtained by substituting $\sin i$ for $\frac{v_1}{v_2}$ in that given above, and reduces to

$$h = \frac{\Delta'}{2} \cdot \frac{(1 - \sin i)}{\cos i}$$

In the practical application of the refraction method the recording instruments are set up at different distances from the explosion, and the travel-times of the first onsets are

graphed. If Δ' lies within the range of distances to the recorders the graph consists of two straight lines; the first starts from the origin at the time of the explosion and shows the travel of the direct waves, the second at a steeper slope commences from Δ', the point where the refracted wave catches up the direct one. The slopes of the two lines give the velocities in the upper and lower layers and the depth of the discontinuity is obtained from the velocities and the distance Δ'. The method can be extended for three or more layers, just as we do in the analysis of the seismograms for near earthquakes.

In a modified form the method can be used when the surfaces separating the media are not horizontal. If the discontinuity between two media is inclined at an angle α to the horizontal

$$\frac{v_1}{v_2} = \sin(i + \alpha)$$

and the relation between h and Δ' becomes

$$h = \frac{\Delta'}{2} \frac{1 - \sin(i + \alpha)}{\cos i \cos \alpha}$$

The angle α is regarded as positive if the discontinuity slopes downwards, and negative if the slope is upwards. In either case the values of h and α can both be calculated from the results of observations taken in both directions.

The velocities and the depths of the discontinuities are obtained from the experiments. The composition at different depths is determined by comparing the velocities with the known values for different materials. The velocity in any of the superficial formations of the earth's crust varies from place to place, according to local peculiarities of consolidation, water content, etc., and geological information regarding the probable structure is frequently applied to confirm the identifications from the velocities. The following values are given by Gutenberg as fairly typical for the velocities of longitudinal waves in materials near the earth's surface.

VELOCITIES OF LONGITUDINAL WAVES (KM./SEC.)

Dry gravel	$\frac{1}{2}$–1	Sandstone	2–2$\frac{1}{2}$
Dry sand	$\frac{1}{2}$–1	Schist	3
Wet loam	$\frac{3}{4}$–1	Chalk	3$\frac{1}{4}$–4
Wet sand	$\frac{3}{4}$–1$\frac{1}{4}$	Ice	3$\frac{1}{2}$
Sandy clay	1–1$\frac{1}{4}$	Salt	4$\frac{1}{2}$–5$\frac{1}{4}$
Water	1·4–1·5	Granite	4$\frac{3}{4}$–5$\frac{3}{4}$
Limestone	1$\frac{1}{2}$–2	Basalt	5–6

EXPERIMENTAL PROCEDURE

At the shot-point the explosive is generally placed at the bottom of a hole several feet deep ; the amount of explosive used varies from a fraction of a pound to about a ton depending on the surroundings and the distances to which recording is required. The magnitude of the earth waves generated from the explosion varies with the type and amount of charge, the depth to which it is buried and the material in the vicinity. Larger charges are required if the surroundings are porous or spongy than for rocky regions, and better results are obtained by filling the hole which contains the explosive with water. The charge is exploded electrically from a safe distance, and the instant of explosion is transmitted by wireless time signal operated from the firing mechanism and recorded in the seismograms. To obtain the fullest information possible without unnecessary extravagance in explosives records of each explosion are taken with several seismographs. For this purpose it is usually most convenient to use from four to six instruments, distributed either in a fan-shaped arrangement or along a straight line.

The requirements in recording the waves from explosions differ in many respects from those in earthquake recording. The fundamental distinction between the two problems is that in prospecting the explosion occurs at a known time and the instruments need only be in operation for short intervals, whereas the times of occurrence of earthquakes cannot be anticipated and the normal seismological recording has to be continuous.

The seismographs used in prospecting must be of robust

construction so that they can be moved about without damage, and the adjustments needed when the instruments are set up should be as simple as possible. The seismographs are not kept in operation long enough for slow drifts of the pendulums, caused by temperature changes or tidal effects, to be serious, and the magnification can be large enough to record the waves from comparatively small charges. The free periods of the pendulums are very short, being usually only a fraction of a second. Damping of the pendulums is unnecessary for the refraction method in which only the first onsets are required, but the reflexion method can only be used with well-damped pendulums otherwise the reflected waves would be obscured by the later oscillations from the much larger direct waves.

In the vertical seismograph used by Mintrop a heavy lead sphere is carried by a horizontal spring. The top of an aluminium cone attached above the weight rubs against a vertical spindle carrying the mirror which is rotated when the weight is displaced. The rotation of the mirror is recorded photographically. In addition to the rotation of the mirror, the record shows the instant of the explosion recorded from a wireless time signal, and uniform time intervals from the oscillations of a pendulum incorporated in the recorder.

W. Schweydar designed an instrument in 1926 for recording the horizontal and vertical components on the same record. In his pendulums the connexions between the tops of the cones and the mirrors are each made by a hair attached to the cone and passing round the mirror spindle. The free period is 0·07 second but can be reduced to 0·025 second if the reflexion method is being used. Normally the magnification is about 25,000 ; an additional mirror can be inserted to double the length of the light beam and the magnification.

The seismograph brought out by J. H. Jones in 1929 is another modification of the vertical Mintrop instrument. The mirror is attached to a small piece of soft iron which is

carried on a phosphor-bronze strip suspended from the cone. The soft iron is located in a non-uniform magnetic field, in such a position that the direction of the lines of force around the iron changes considerably if the element is displaced. The soft iron tends to set itself along the lines of force and small movements of the cone are accompanied by large deflexions of the mirror. Oil damping is provided for the pendulum which has a free period of about $\frac{1}{4}$ second. The cone magnifies the ground movement between 8 and 9 times and a total magnification of about 50,000 can be obtained.

These instruments, and other types which have been evolved on the lines of the conventional seismographs, must be placed on the surface of the ground where they are affected by wind and other disturbances. Further disadvantages in connexion with their use for prospecting are that the sensitivity cannot be easily adjusted to suit the particular conditions for any explosion, and that a separate photographic recorder is required at each point of observation. These disadvantages have been overcome by the adoption of electrical detectors, called "geophones," which operate through an amplifier to an oscillograph or a sensitive galvanometer.

The Schweydar geophone consists of a hollow cylinder, of length 7 inches and diameter $4\frac{1}{2}$ inches, containing an electromagnet and an induction coil. The coil is attached to a diaphragm covering the lower end of the cylinder and moves between the poles of the magnet when the diaphragm is disturbed. The free period of oscillation is about a tenth of a second. The coil is connected to the recording instrument which may be situated at a considerable distance from the geophone. The geophone must be used under water, and for land surveys is suspended in a hole three or four feet deep which is filled with water.

For prospecting by the reflexion method in 1935 the Anglo-Iranian Oil Company used geophones in which a coil attached to the case is placed between the poles of a large magnet supported on a helical spring. The position of the

coil in the magnetic field changes when the ground moves, and a current is generated in the coil; the current after passing through a three-valve amplifier is large enough to be recorded with a string galvanometer.

In their experiments testing the seismographic method for determining the crustal structure, Gutenberg, Wood and Buwaldo, working in central and southern California, used

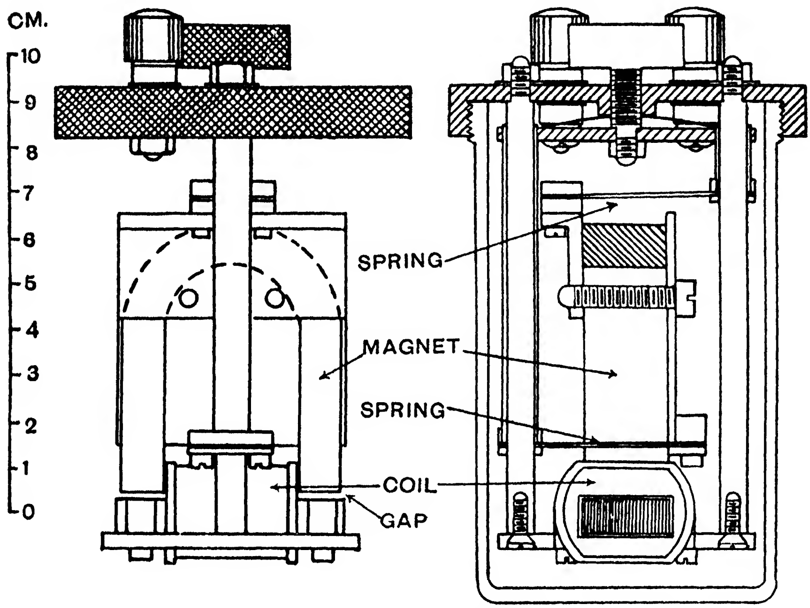


FIG. 79.—Geophones of the type designed by E. C. Bullard and C. Kerr Grant

six geophones which were buried in the ground at different points and connected by cables to the amplifiers. To facilitate the removal of the apparatus from place to place without complete dismantling, the amplifiers and registering mechanism were installed on a lorry which served as the central station. The amplified currents from the geophones were all shown on one record by using a string galvanometer with six elements, an arrangement which is particularly convenient for accurate comparisons of the times of the onsets at the different instruments.

An improved type of geophone has recently been designed by E. C. Bullard and C. Kerr Grant of the Department of Geodesy and Geophysics, University of Cambridge. The instrument is shown in Fig. 79. The principle employed is similar to that of the Benioff vertical seismograph (page 70), the length of an air gap between a magnet and armature being changed by the ground movements. The magnet, carried by two leaf springs, is movable, whilst the coil is attached to the framework of the instrument. The case is filled with oil to above the level of the gap to provide the necessary damping. The coil is connected to the grid of the first amplifying valve. With suitable amplifiers it is possible to increase the magnification to a thousand million or more, but in practice owing to the incidence of spurious disturbances a magnification of about one million is as high as can conveniently be used. Specimens of the records which have been obtained with geophones of this type appear in Figs. 80 and 81. The first of these diagrams shows the records of an explosion at five different distances arranged in order of the distance from the explosion to the geophone. The distances are all in the range where the refracted waves arrive before the direct waves. For each distance the onset of the refracted waves is shown as a small movement in the first part of the record, followed by the much stronger onset of the direct waves. In the other diagram the top record (*a*) was taken from a geophone placed on a stone slab which was placed on a motor-car inner tube, and shows the disturbance produced by dropping a lead shot on to the slab. This minute shock is sufficient to make the slab sway on the tyre and also to set up elastic vibrations in the stone; the slow undulations in the record are due to the swaying, and rapid oscillations to the elastic waves. The two smaller disturbances shown later in the record indicate the impacts of the shot on the slab after bouncing. The centre record (*b*) shows the disturbance recorded when a weight was dropped 5 metres from a geophone buried in a field. The bottom one (*c*) is the record

from an explosion of 10 lbs. of gelignite at a distance of 6,200 feet. The onsets of a number of waves are indicated on the record by the letters A, B, C, D, E. According to Dr. Bullard and Mr. Kerr Grant A is the refracted wave, E the direct wave, and the intermediate onsets are of refracted waves which have undergone several reflexions at the surface and at the subjacent discontinuity.

Several other electrical devices have been applied to the detection of the seismic waves from explosions; among

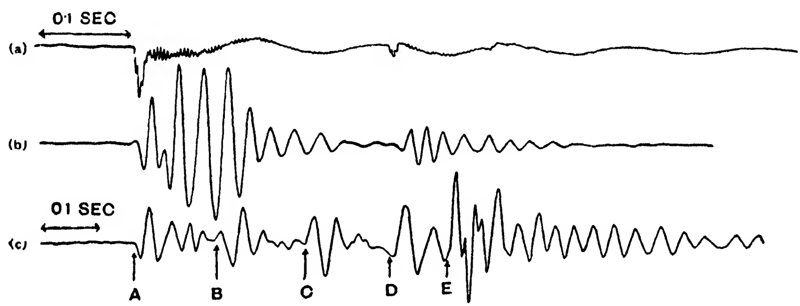


FIG. 81.—Record of various ground motions (Bullard and Grant)

these may be mentioned the microphones used for picking up sound waves, and instruments depending on measurements of electrical capacity or of the piezo-electric effect. Details of most of the instruments designed for commercial use have not been published. Gutenberg has pointed out that this reticence has arisen "doubtless because of a disinclination to make the exact nature of the methods and instruments a matter of common knowledge".

Special photographic recorders must be used to obtain a sufficiently open time-scale for the recording of explosions. The photographic paper or film is driven through the recorder by a clockwork or electrical motor, and the exposed film is passed through baths for developing, fixing and washing, so that the records can be inspected within a few minutes of the explosion. Askania-Werke manufacture a very convenient recorder of this type which can be used

with the earlier prospecting seismographs or with geophones. In this recorder the paper speed can be varied from 3·5 to 8 cms. per second.

The installations of the instruments at the firing point and at one of the receiving stations are shown in two illustrations from the Askania-Werke pamphlet which are reproduced in Fig. 82. The apparatus for exploding the charge, and for transmitting the instant of the explosion by wireless telegraphy, appear in the foreground of the upper picture; the lower shows the seismograph and recorder, together with the wireless set for reception and amplification of the firing signal which is indicated by a sharp break in a separate line of the record.

Results Obtained on Land

It is natural that at first the seismic methods should have been utilized solely in connexion with prospecting on land, for the seismographs could only be used when placed on reasonably firm ground. Geophones too were used initially on land but it was soon realized that these detectors, recording at a distance, might also be employed for observations of the structure beneath lakes or at sea near the coasts. The first observations for water-covered regions were made in 1927.

On land the methods have proved successful in many parts of the world. The most important practical applications are connected with endeavours to locate the natural reservoirs of oil which are frequently found on the sides of salt domes. These domes are large masses of rock salt which intrude from great depths into unconsolidated sediments. There is a considerable difference between the speeds of the seismic waves in the salt and in the sediments, and the domes can be surveyed effectively by the seismic method. The results obtained in surveys carried out for commercial purposes are not generally available but valu-

able data have been published for scientific investigations in which the methods have been tested and applied.

Some interesting experiments were made in south-east England by the scientific staff of the Anglo-Iranian Oil Coy. during the summer of 1929. The object of the tests was to estimate the thickness of the layers of gravel, sand and clay over the chalk at the Chobham Ridges near Bagshot in Surrey. The Jones and similar types of seismographs were used for making a survey over a distance of 2 km. from Cæsar's Camp to Lower Star Post. The explosive was gelignite in charges which varied from 1 to about 15 lb. The times of the first onsets were plotted against the distance and it was found that at a distance of about 0·8 km. from the explosions the velocity increased from 1·8 km./sec. to 3·3 km./sec. The higher velocity is within the range given by Gutenberg for chalk (p. 217), but that of the direct wave is rather higher than his values for the superficial clay, etc. On substitution in the formula $h = \frac{\Delta'}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}}$ of the observed velocities and the distance to the point at which the direct and refracted waves arrive simultaneously, it is found that the depth to the chalk is about 0·23 km. (750 ft.). The results of tests carried out in either direction showed that there were differences over the whole of the traverse of about 0·03 km. (100 ft.) in the depth to the chalk; this variation, appears reasonable since the survey was made in undulating country, and the chalk outcrops about 15 km. to the south. The depth to the chalk at Chobham Ridges is about the same as that found from direct observations in the construction of an artesian well at Virginia Water, about 10 km. away to the east-north-east. In boring this well, which is carried to a depth of 1,416 ft., the mottled clay was reached at 483 ft., chalk and flints at 716 ft., and the upper greensand at 1,164 ft.

A considerable amount of information regarding the structure in selected regions was obtained by Gutenberg, Wood and Buwalda, in their tests of the utility of the seismic

methods for prospecting. The regions of California covered in these tests are the Owens Valley, the Yosemite Valley, the Los Angeles Basin and the Ventura Basin. The valleys are mountainous regions where the sediments are thin and the structure is broken by numerous faults ; the sediments extend to very great depths in the basins. The observations near the mountains show that faults, even when they are entirely concealed beneath the surface, can be detected by the seismic surveys. In favourable circumstances the displacements at the faults can be estimated. Large charges, with recording distances exceeding 8 km., were used for the surveys over thick sediments, but no waves which had reached the granite could be detected. The observations by the refraction method indicated a number of layers at depths to about 2 km. ; the reflected waves confirmed the existence of some of these discontinuities and showed others at depths to about 4 km., but the granite was not reached. The velocities in the sediments of the Ventura Basin, about 100 km. west of Los Angeles, were about the same as those in the Los Angeles Basin.

The effectiveness of geophysical methods in dealing with the problems of prospecting in Australia was thoroughly tested in the years 1928–30. The investigations were carried out by the Imperial Geophysical Experimental Survey, appointed by the British Empire Marketing Board and the Commonwealth Government, which each contributed £16,000 towards the cost. Magnetic, electrical, gravimetric and seismic methods were examined. In the seismic work the normal procedure was followed for the explosions. The receiving apparatus available consisted of a Schweydar two component seismograph and an installation of six geophones recording on a six-string Einthoven galvanometer. In some tests the receiving stations were set up on a line through the explosion point, in others a radial distribution was adopted. The observations were made in two localities, the Gulgong gold field and the Tallong district, both in New South Wales. The bed rock of granite and slate in the

Gulgong region is overlaid by sands, clays and pebble beds. The thicknesses of the alluvium, which did not exceed 250 ft., were known from borings in the vicinity. The depths obtained by the refraction observations are in satisfactory agreement with the measured values. There are a great variety of geological materials and structures in the Tallong district ; the velocities obtained for the longitudinal waves in a number of materials are :

	km./sec.		km./sec.
Wet loam	0·8	Hard clay-slate	3·2–3·5
Cemented sand	0·9–1·0	Hornfels slates	3·5–4·4
Sandy clay	1·0–1·2	Granodiorite	4·6
Cemented sandy clay	1·2–1·3	Granite	5·6
Sandstone conglomerate	2·4		

The observations indicate that the velocity may vary over a considerable range for formations which are geologically similar. The conclusion, drawn from the seismic observations in Australia, is that the methods may safely be utilized for the study of extended stratifications, of large intrusions, or of the simpler characteristics beneath the surface ; they are not suitable, however, for investigation of minor variations in the structure, which can easily be obscured by the irregularities in the velocities for the surface layers.

Submarine Prospective

The earliest observations of the propagation of the waves from explosions in regions under water were followed in 1928 by a survey of the coastal lakes of Louisiana. The water was less than 20 ft. deep, and by using long poles the geophones could be embedded in the mud at the bottom of the lakes. A party of American scientists led by M. Ewing of Lehigh University has modified the procedure so that the seismic methods can be used in water of depths as great as 100 fathoms.[1] In the experiments at sea the explosive and geophones are both lowered to the ocean

[1] The ocean floor slopes gradually down from the coast to a depth of about 100 fathoms and then sharply to much greater depths, the 100 fathom line being usually regarded as the edge of the continental shelf.

floor, the former from a small boat by the firing cable, and the latter from a ship in which the recording mechanism is installed. The distances from the explosion to the recorders can be calculated from the time of travel of the longitudinal waves propagated through the water.

Experiments were made in 1935 at sea, near Woods Hole, Massachusetts, and along a profile extending across the Coastal Plain of Virginia from Petersburg to Cape Henry, and thence in an easterly direction to the edge of the continental shelf about 100 km. from the coast. The observations at sea were made on the *Oceanographer*, a ship belonging to the United States Coast and Geodetic Survey, and on the *Atlantis* of the Woods Hole Oceanographic Institution.

The results obtained for both regions are in good agreement, indicating that around the eastern coasts of the United States the crystalline rocks are overlain by two main layers of sediments. The velocities of the longitudinal waves vary from 5·2 to 6·1 km./sec. in the underlying rocks, from 2·0 to 2·6 km./sec. in the lower layer of sediments, and from 1·5 to 1·8 km./sec. in the upper layer. These velocities, combined with a knowledge of the geological structure on land near the coast, serve for provisional identification of the materials. It appears that the deepest rocks are granitic, that the lower layer consists of Triassic and Jurassic formations, and the upper one of Cretaceous and more recent sediments. The thicknesses of the sediments and the depths of the ocean, for the section from Petersburg to the eastwards across Cape Henry, are illustrated in Fig. 83.

On the western side of the coastal plain and towards the continental shelf the upper sediments are very thin. The greatest thickness of these sediments occurs on the seaward side of the coastline and is only about half a kilometre. The total thickness of sediments increases from about 0·1 km. near Petersburg to 0·9 km. near the coast ; east of the coast the sediments extend to greater depths, the thickness increasing to about 4 km. near the edge of the continental shelf. The average slope of the upper surface of the granitic rock

is about 1 in 150 on the landward part of the profile and 1 in 35 on the seaward part. Thus the upper surface of the basic rocks beneath the American Continent is depressed in the region from the coast to the continental shelf, and the sediments over the depressed part are of enormous thickness.

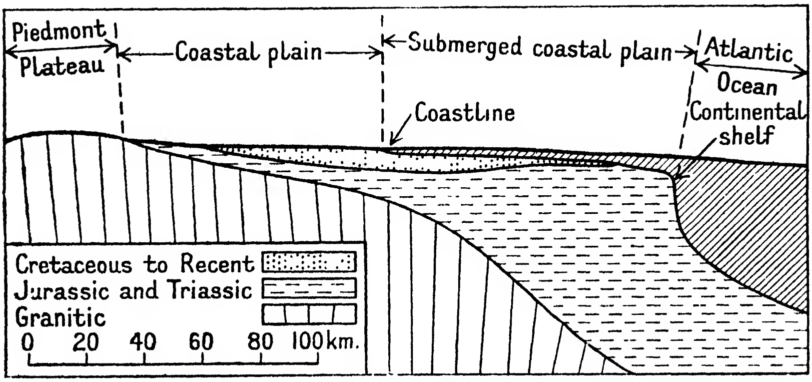


FIG. 83.—Section from the Piedmont Plateau across the coastal plain of Virginia to the Atlantic Ocean

These results are a most important contribution to our knowledge of the structure of the region concerned, but alone they cannot provide a solution of many fundamental questions regarding the development of the continents and oceans. The great need at the present stage is to accumulate further information; the observations must be made in many other regions, for greater depths in the earth's crust, and for the rocks beneath the deep ocean. The problem of working in deep water is a very difficult one, but apparently the seismic methods are the only means by which information can be obtained about the rocks in these regions.

Chapter XVI

SUMMARIES: FACTS AND FORMULÆ, RECENT IMPORTANT EARTHQUAKES, SEISMOLOGICAL LITERATURE

In this concluding Chapter are gathered together some of the important facts and formulæ relating to the earth and the travel of seismic waves, the list of the earthquakes which were recorded in Britain with amplitudes greater than 0·1 mm. from the beginning of 1915 to the middle of 1938, and a selection of publications which may be of assistance to those who require further information. The works referred to in the last of these sections are mostly of a comprehensive nature; original papers have only been included when the information contained in them has not yet been treated adequately in the text-books. If references to other works are needed, the *Bibliography of Seismology* prepared by E. A. Hodgson and published from the Dominion Observatory, Ottawa, may be consulted; this bibliography has been issued at quarterly intervals since 1929 and so far contains references to about four thousand works.

The Earth

Equatorial radius:	6,378 km. = 3,963 miles.
Polar radius:	6,357 km. = 3,950 miles.
Quadrant of circumference:	90° = 10,000 km. = 6,215 miles.
Mass:	$5{\cdot}98 \times 10^{27}$ grams.
Volume:	$1{\cdot}083 \times 10^{21}$ cubic metres.
Mean density:	5·5 grams per c.c.
Area of land:	$1{\cdot}45 \times 10^{18}$ square cms.
Area of ocean:	$3{\cdot}67 \times 10^{18}$,, ,,
Depth from surface to boundary of central core:	2,900 km.

Calculation of distance, Δ, between two points from the direction cosines :

$$a = \cos\phi_1 \cos\lambda_1, \quad b = \cos\phi_1 \sin\lambda_1, \quad c = \sin\phi_1,$$
$$A = \cos\phi_2 \cos\lambda_2, \quad B = \cos\phi_2 \sin\lambda_2, \quad C = \sin\phi_2.$$
$$2(1 - \cos\Delta) = (a - A)^2 + (b - B)^2 + (c - C)^2$$
$$\cos\Delta = aA + bB + cC.$$

Calculation of epicentre, ϕ_E, λ_E, given the distance, Δ, and bearing, α, from a given observatory, ϕ_S, λ_S :

$$\sin\phi_E = \sin\phi_S \cos\Delta + \cos\phi_S \sin\Delta \cos\alpha$$
$$\sin\,(\lambda_E - \lambda_S) = \frac{\sin\Delta \sin\alpha}{\cos\phi_E}.$$

Formulæ for stereographic projection :

$$r = \frac{R \sin\Delta}{\sin\phi + \cos\Delta}$$
$$d = \frac{R\cos\phi}{\sin\phi + \cos\Delta}.$$

Greatest vertical displacement of the ground due to an earthquake : 47 ft. 4 in. ($14\frac{1}{2}$ metres) in the Alaska earthquake of 10th September, 1899.

Greatest depth of focus on record : 720 km. for the earthquake on 29th June, 1934, with epicentre in the Flores Sea.

Elasticity and the Propagation of Seismic Waves

Relations between k (incompressibility), n (rigidity), E (Young's modulus), and σ (Poisson's ratio) :

$$E = \frac{9kn}{3k + n}, \qquad \sigma = \frac{3k - 2n}{6k + 2n}$$
$$k = \frac{E}{3(1 - 2\sigma)}, \quad n = \frac{E}{2(1 + \sigma)}.$$

If $\sigma = 0{\cdot}25$: $k = \frac{2}{3}E$, $n = \frac{2}{5}E$, $n = \frac{3}{5}k$.

Velocities of waves in a solid of density, ρ, incompressibility, k, and rigidity, n :

Longitudinal $\sqrt{\dfrac{k + \frac{4}{3}n}{\rho}}.$

Transverse $\sqrt{\dfrac{n}{\rho}}.$

Rayleigh $0{\cdot}919\sqrt{\dfrac{\mu}{\rho}}.$

If $\sigma = 0{\cdot}25$ the velocities of longitudinal and transverse waves are in the ratio $\sqrt{3} : 1$.

Velocity of longitudinal waves in fluid: $\sqrt{\dfrac{k}{\rho}}$.

Laws of Reflexion and Refraction (Fig. 31)

$$\sin\theta : \sin\phi : \sin\theta' : \sin\phi'$$
$$= \sqrt{\frac{k+\frac{4}{3}n}{\rho}} : \sqrt{\frac{n}{\rho}} : \sqrt{\frac{k'+\frac{4}{3}n'}{\rho'}} : \sqrt{\frac{n'}{\rho'}}.$$

Velocities of waves in the earth's crust:

P_g	5·57 km./sec.	S_g	3·36 km./sec.
P*	6·50 km./sec.	S*	3·74 km./sec.
P	7·76 km./sec.	S	4·36 km./sec.

Velocity of longitudinal waves in water at 0° C.: 1·40 km./sec.

Formulæ for use in Seismic Prospecting

Times of travel of waves to distance Δ with a horizontal discontinuity at depth h:

Direct waves $\dfrac{\Delta}{v_1}$

Reflected waves $\dfrac{1}{v_1}\sqrt{4h^2+\Delta^2}$

Refracted waves $\dfrac{1}{v_2}\left\{\Delta + 2h\sqrt{\left(\dfrac{v_2}{v_1}\right)^2 - 1}\right\}$

Reflected and refracted waves arrive simultaneously when

$$\Delta' = 2h\sqrt{\frac{v_2+v_1}{v_2-v_1}} = 2h\frac{\cos i}{1-\sin i}.$$

For a discontinuity inclined at an angle α to the horizontal:

$$\Delta' = 2h\,\frac{\cos i\cos\alpha}{1-\sin(i+\alpha)}.$$

Recent Important Earthquakes

List of Earthquakes Producing Movements Greater than 0·1 mm. in Britain (January, 1915–June, 1938)

No.	Date	Co-ordinates of Epicentre	Locality
1	1915, Sept. 7th	15° N., 91° W.	Guatemala
2	Oct. 3rd	37° N., 118° W.	California
3	Nov. 1st	38° N., 144° E.	East of Japan
4	1916, Jan. 13th	3° S., 138° E.	North-west of New Guinea
5	Jan. 24th	41° N., 37° E.	Asiatic Turkey
6	Feb. 1st	29° N., 131° E.	Riu-Kiu Islands
7	Feb. 27th	11° N., 91° W.	Pacific Ocean west of Nicaragua
8	1917, May 9th	11° N., 144° E.	Pacific Ocean south-east of Guam
9	May 31st	55° N., 160° W.	South of Alaska Peninsula
10	July 4th	25° N., 123° E.	North-east of Formosa
11	July 29th	3° S., 143° E.	New Guinea
12	1918, July 8th	27° N., 92° E.	Bhutan
13	Dec. 1st	39° N., 73° E.	Pamir Plateau
14	1919, Jan. 1st	5° N., 125° E.	Celebes Sea south of Mindanao
15	May 3rd	41° N., 146° E.	East of Japan
16	1920, June 5th	24° N., 120° E.	Formosa Strait
17	1922, Jan. 31st	41° N., 127° W.	Pacific Ocean west of northern California
18	Apr. 8th	72° N., 9° W.	Arctic Ocean north-west of Jan Mayen
19	Aug. 13th	36° N., 28° E.	Rhodes
20	Sept. 1st	25° N., 121° E.	Northern Formosa
21	1923, Mar. 2nd	6° N., 125° E.	South of Mindanao
22	Mar. 24th	31° N., 101° E.	South-eastern Tibet
23	May 4th	55° N., 157° W.	South of Alaska Peninsula
24	June 22nd	23° N., 99° E.	Yun-nan, China
25	Sept. 1st	35° N., 139° E.	Japan
26	Sept. 9th	25° N., 91° E.	Western Assam
27	Oct. 7th	1° S., 129° E.	Molucca Islands
28	1925, Apr. 16th	22° N., 121° E.	Formosa
29	May 3rd	3° N., 127° E.	Molucca Islands
30	1926, Jan. 25th	9° S., 159° E.	Solomon Islands
31	Feb. 8th	12° N., 89° W.	Pacific Ocean south of Salvador
32	Mar. 18th	35° N., 29° E.	Mediterranean Sea south-east of Rhodes
33	Apr. 12th	11° S., 161° E.	Solomon Islands
34	June 26th	36° N., 28° E.	Rhodes
35	Aug. 30th	37° N., 23° E.	Greece
36	Sept. 10th	9° S., 111° E.	Indian Ocean south of Java
37	Sept. 19th	35° N., 22° E.	Mediterranean Sea west of Crete
38	Oct. 3rd	51° S., 161° E.	Pacific Ocean north of Macquarrie Island

No.	Date	Co-ordinates of Epicentre	Locality
39	Oct. 26th	3° S., 139° E.	North-west of New Guinea
40	1927, Mar. 7th	36° N., 135° E.	Sea of Japan
41	May 22nd	37° N., 103° E.	Kan-su, China
42	June 3rd	7° S., 131° E.	Banda Sea
43	July 1st	37° N., 23° E.	Greece
44	Aug. 5th	39° N., 143° E.	East of Japan
45	Sept. 11th	45° N., 35° E.	Crimea
46	Oct. 24th	56° N., 136° W.	Pacific Ocean near southern Alaska
47	Nov. 4th	35° N., 121° W.	Pacific Ocean near California
48	Dec. 28th	54° N., 161° E.	Kamtchatka
49	1928, Mar. 9th	2° S., 89° E.	Indian Ocean west of Sumatra
50	Mar. 16th	23° S., 171° E.	Pacific Ocean south-east of Loyalty Islands
51	Mar. 22nd	16° N., 96° W.	South of Mexico
52	Mar. 27th	47° N., 13° E.	Southern Austria
53	Mar. 31st	39° N., 28° E.	Asia Minor
54	Apr. 14th	42° N., 26° E.	Bulgaria
55	Apr. 18th	42° N., 26° E.	,,
56	Apr. 22nd	38° N., 23° E.	Greece
57	May 2nd	40° N., 29° E.	Asia Minor
58	May 14th	5° S., 78° W.	Northern Peru
59	May 27th	40° N., 142° E.	East of Japan
60	June 17th	16° N., 97° W.	South of Mexico
61	July 18th	5° S., 79° W.	Northern Peru
62	Aug. 4th	16° N., 97° W.	South of Mexico
63	Oct. 9th	16° N., 97° W.	,, ,, ,,
64	Oct. 15th	29° N., 66° E.	Baluchistan
65	Dec. 1st	34° S., 73° W.	Pacific coast of Chile
66	Dec. 19th	7° N., 125° E.	Mindanao
67	1929, Jan. 13th	50° N., 155° E.	Kurile Islands
68	Feb. 22nd	11° N., 43° W.	Atlantic Ocean north of Brazil
69	Mar. 7th	49° N., 170° W.	Pacific Ocean south of Aleutian Islands
70	May 1st	38° N., 57° E.	Northern Persia
71	May 18th	39° N., 37° E.	Asia Minor
72	May 26th	50° N., 131° W.	Pacific Ocean near British Columbia
73	June 16th	42° S., 172° E.	Murchison, New Zealand
74	June 27th	54° S., 30° W.	Atlantic Ocean north of Sandwich Group
75	July 7th	51° N., 178° E.	Aleutian Islands
76	Nov. 15th	8° N., 143° E.	Caroline Islands.
77	Nov. 18th	45° N., 56° W.	Atlantic Ocean south of Newfoundland
78	Dec. 17th	53° N., 171° E.	Aleutian Islands
79	1930, May 5th	17° N., 97° E.	Burma
80	May 6th	37° N., 44° E.	Kurdistan

No.	Date	Co-ordinates of Epicentre	Locality
81	July 2nd	26° N., 90° E.	Western Assam
82	July 23rd	41° N., 15° E.	Southern Italy
83	Sept. 21st	25° N., 99° E.	Yun-nan, China
84	Oct. 24th	18° N., 147° E.	Marianne Islands
85	Nov. 25th	35° N., 139° E.	Japan
86	Dec. 3rd	18° N., 96° E.	Burma
87	1931, Jan. 15th	16° N., 96° W.	South of Mexico
88	Jan. 27th	25° N., 97° E.	Northern Burma
89	Jan. 28th	11° N., 145° E.	Pacific Ocean south-east of Guam
90	Feb. 2nd	39° S., 177° E.	Hawke's Bay, New Zealand
91	Feb. 13th	39° S., 177° E.	,, ,, ,, ,,
92	Mar. 8th	41° N., 23° E.	Greece
93	Mar. 9th	41° N., 143° E.	East of Japan
94	May 20th	37° N., 16° W.	Atlantic Ocean between the Azores and Portugal
95	June 7th	54° N., 1° E.	North Sea
96	Aug. 10th	47° N., 90° E.	Great Altai Mountains, Mongolia
97	Aug. 18th	47° N., 90° E.	,, ,, ,, ,,
98	Aug. 24th	30° N., 68° E.	Baluchistan
99	Aug. 27th	30° N., 67° E.	,,
100	Sept. 25th	5° S., 103° E.	Indian Ocean near south-west of Sumatra
101	Oct. 3rd	11° S., 162° E.	Solomon Islands
102	Nov. 2nd	16° N., 97° W.	South of Mexico
103	1932, May 14th	1° N., 126° E.	Molucca Passage
104	May 26th	24° S., 179° E.	Pacific Ocean south of Fiji Islands
105	June 3rd	19° N., 104° W.	Western coast of Mexico
106	June 18th	19° N., 104° W.	,, ,, ,, ,,
107	Sept. 26th	40° N., 24° E.	Chalcidice Peninsula, Greece
108	Sept. 29th	40° N., 23° E.	Gulf of Salonica
109	Dec. 21st	39° N., 118° W.	Nevada
110	Dec. 25th	39° N., 96° E.	Nan-shan Mountains, Central Asia
111	1933, Feb. 23rd	20° S., 71° W.	Pacific Ocean near northern Chile
112	Mar. 2nd	40° N., 145° E.	East of Japan
113	Apr. 27th	61° N., 150° W.	South of Alaska
114	June 18th	39° N., 143° E.	East of Japan
115	June 24th	5° S., 104° E.	South-west of Sumatra
116	Aug. 25th	31° N., 103° E.	Sze-chwan, China
117	Aug. 28th	58° S., 27° W.	South Atlantic, Sandwich Group
118	Nov. 20th	73° N., 70° W.	Baffin Bay
119	1934, Jan. 15th	26° N., 86° E.	North Bihar
120	Feb. 14th	18° N., 118° E.	North-west of Luzon
121	Mar. 5th	41° S., 177° E.	Near the east coast of New Zealand
122	Apr. 15th	8° N., 127° E.	Near the east coast of Mindanao

No.	Date	Co-ordinates of Epicentre	Locality
123	July 18th	8° N., 83° W.	Pacific Ocean near southern Costa Rica
124	July 18th	17° S., 167° E.	New Hebrides
125	July 21st	18° S., 164° E.	Coral Sea west of New Hebrides
126	Dec. 15th	31° N., 89° E.	Southern Tibet
127	Dec. 31st	30° N., 116° W.	Lower California
128	1935, Jan. 4th	41° N., 28° E.	Sea of Marmara
129	Apr. 19th	33° N., 16° E.	Mediterranean Sea near Tripoli
130	Apr. 20th	25° N., 121° E.	North-west of Formosa
131	May 30th	30° N., 67° E.	Near Quetta, Baluchistan
132	Sept. 4th	23° N., 121° E.	Formosa
133	Sept. 11th	45° N., 147° E.	Kurile Islands
134	Sept. 20th	4° S., 141° E.	New Guinea
135	Oct. 12th	41° N., 147° E.	Kurile Islands
136	Oct. 18th	44° N., 147° E.	,, ,,
137	Dec. 14th	14° N., 93° W.	Pacific Ocean near Guatemala
138	Dec. 15th	10° S., 163° E.	Solomon Islands
139	Dec. 17th	22° N., 127° E.	Pacific Ocean east of Formosa
140	Dec. 28th	0°, 98° E.	Indian Ocean near western Sumatra
141	1936, Apr. 1st	3° N., 123° E.	Celebes Sea.
142	Apr. 19th	9° S., 156° E.	Solomon Islands
143	May 27th	29° N., 84° E.	Himalayas
144	June 30th	51° N., 160° E.	Pacific Ocean south of Kamtchatka
145	July 13th	24° S., 71° W.	Pacific Ocean near northern Chile
146	Aug. 22nd	22° N., 121° E.	Formosa
147	Nov. 2nd	38° N., 142° E.	East of Japan
148	Nov. 13th	56° N., 165° E.	Pacific Ocean east of Kamtchatka
149	1937, Jan. 7th	35° N., 97° E.	Eastern Tibet
150	Feb. 21st	45° N., 148° E.	Kurile Islands
151	Apr. 16th	22° S., 179° E.	Pacific Ocean south of Fiji Islands
152	July 22nd	65° N., 147° W.	Fairbanks, Alaska
153	Aug. 20th	17° N., 122° E.	Northern Luzon
154	Sept. 3rd	52° N., 177° W.	Aleutian Islands
155	Dec. 23rd	15° N., 98° W.	Pacific Ocean near southern Mexico
156	1938, Feb. 1st	4° S., 131° E.	Banda Sea
157	Apr. 19th	39° N., 33° E.	Asia Minor
158	May 12th	5° S., 147° E.	East of New Guinea
159	May 19th	1° S., 119° E.	Macassar Strait
160	May 23rd	36° N., 131° E.	Sea of Japan
161	June 10th	25° N., 125° E.	Riu-Kiu Islands
162	June 11th	51° N., 4° E.	Belgium
163	June 16th	29° N., 128° E.	Riu-Kiu Islands
164	June 20th	37° N., 77° E.	Karakoram Mountains, Central Asia

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INDEX

(*i*) *Subjects*

(ii) Names